ARCHITECTURAL CONSIDERATIONS FOR SINGLE OPERATOR MANAGEMENT OF MULTIPLE UNMANNED AERIAL VEHICLES

THESIS

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Abstract

Recently, small Unmanned Aircraft Systems (UAS) have become ubiquitous in military battlefield operations due to their intelligence collection capabilities. However, these unmanned systems consistently demonstrate limitations and shortfalls with respect to size, weight, range, line of sight and information management. The United States Air Force Unmanned Aircraft Systems Flight Plan 2009-2047 describes an action plan for improved UAS employment which calls out single operator, multi-vehicle mission configurations. This thesis analyzes the information architecture using future concepts of operations, such as biologically-inspired flocking mechanisms. The analysis and empirical results present insight into the engineering of single-operator multiple-vehicle architectures.

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Gabriel T. Bugajski

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I. Introduction

1.1 Thesis Introduction

In the last decade, the Department of Defense (DoD) has increasingly relied on Unmanned Aircraft Systems (UAS). The United States Air Force (USAF) achieved a milestone by proposing acquisition of more "unmanned aircraft than combat aircraft" in the proposed 2011 fiscal year budget released in February 2010 (Barnes, 2010). The increasing use of UAS for military applications was demonstrated during Operation ENDURING FREEDOM and Operation IRAQI FREEDOM, in which USAF Airmen employed Small UAS of varying platform sizes and capabilities for a variety of missions. However, according to the Air Force Special Operations Command (AFSOC), these unmanned systems consistently demonstrate limitations and shortfalls with respect to size, weight, range, line of sight and information management. The USAF published the USAF Unmanned Aircraft Systems Flight Plan 2009-2047 so as to provide an actionable plan for improving Small, Medium, and Large UAS employment and to address the growing importance of the vehicles. This thesis examines the planned architecture of a single operator controlling multiple Unmanned Aerial Vehicles (UAV).

There are many research areas and challenges pertaining to effective single operator, multiple UAV employment. Topics include human factors engineering, human-computer interface design, usability, aerodynamic modeling and tuning, and maintaining communication between UAVs and between the UAVs and the operator ground station. All of these challenges are roadblocks to the USAF's goal of lowering the number of operators for multiple UAV operations, which has been described in the USAF Flight Plan section titled "Path Toward Full Autonomy" as: "fewer operators will be 'flying' the sorties but directing swarms of aircraft" (Headquarters, United States Air Force, 2009b). Industry leaders and research groups of all types are eagerly working to solve these challenges.

Rapid changes and developments are therefore common and to be expected. Additionally, DoD operations are increasingly requiring joint efforts or as described in the Flight Plan, a "leaner, more adaptable, tailorable, and scalable force that maximizes combat capabilities to the joint force" (Headquarters, United States Air Force, 2009b) is essential to the future of the military. As a result, flexible and integrated solutions to the challenges of single operator management of multiple UAVs are valuable.

To summarize the challenges presented above, a simplification of the problem is considered. First, define an operator as O and a UAV as V. The goal of the USAF dictates that the number of operators required to manage UAVs should decrease as the number of UAVs increase within reasonable boundaries. Due to legal codes, there must be no fewer than one operator that can take control of the multiple UAVs as "humans will retain the ability to change the level of autonomy as appropriate for the type or phase of mission" (Headquarters, United States Air Force, 2009b), and the amount of vehicles under the control of the operator will be dictated by a given scenario. Let this problem then be represented as the minimum of the ratio of operators to vehicles or min(O/V), where the number of operators is fixed at 1. There is no comprehensive solution for how to solve this problem of nearly autonomous operation of UAVs, where nearly autonomous refers to the ability of the group of UAVs to perform a mission with minimal operator management. This thesis addresses the problem by presenting an implementation independent General Information Model that when taken together with artificial intelligence, specifically emergence based flocking, point the way to a permanent solution to the problem of nearly autonomous UAV operation.

While there is no comprehensive solution, efforts have been made to address the various individual challenges inherent in any solution to min(O/V). There is an abundance of research being performed by researchers, for which a short list includes, but not limited to: James Slear's "UAV Swarm Mission Planning and Simulation System" (2006), Dr. David Jacques' cooperative control work titled "Search, Classification and Attack Decisions for Cooperative Wide Area Search Munitions" (2003), and Adrian Phillips' work titled "A Secure Group Communication Architecture For a Swarm of Autonomous Unmanned Aerial Vehicles" (2008). There have been reasonable suggestions for the so-

lution, such as in Johnathan Gabbai's paper "Complexity and the Aerospace Industry: Understanding Emergence by Relating Structure to Performance using Multi-Agent Systems" (Gabbai, 2005). There are even substantial efforts at solving min(O/V) being tested in the field today such as by the company Scientific Systems. Through funding from DARPA, Scientific Systems has "developed and fielded a distributed autonomy software architecture, enabling coordination of multiple heterogeneous autonomous vehicles." This was field tested "in maritime field tests for a fully-autonomous, collaborative field comprising up to 40 unmanned vehicles" (Komerska *et al.*, 2009). All of these efforts validate the basic approach of this thesis to the solution.

1.2 Background

The problem of min(O/V) has already been stated, yet the solution has only been broadly described. The solution rests upon the differences between what is termed the Current Model and the proposed Ideal Model which are described in the following subsections.

1.2.1 Current Model. The prevailing method of current single operator multiple UAV operation can be considered as a single system with three different primary parts. The human operator controls the UAVs, which can range in numbers from one to many, through a ground station or interface. Different implementations of the system have varying complexity in that it can be as simple as only a pass through for a few instructions from the operator to the UAVs, or as complex as performing a large amount of the flight mechanics processing for the UAVs. The phrase "the operator controls the UAVs" refers to the operator's interaction with the interface to the UAVs, and how much information the operator must provide through the interface to the UAVs in order for them to function.

The Overhead Watch and Loiter (OWL) system, developed by the AFIT Small Unmanned Aircraft System (SUAS) research team in March 2010 (Seibert *et al.*, 2010), is an excellent example of the Current Model. The OWL system consists of the same three primary pieces as described above; a group of one to many vehicles, an interface or

a ground station, and an operator. The vehicles are electrically powered and able to fly themselves with a small amount of operator interaction through a program which runs on a laptop. This system is defined as the typical operational set-up for single operator multiple UAV operations and is captured in Figure 1.1, which displays a moment when the UAVs are in flight under the management of the operator through a ground station. In this model, the operator controls the multiple UAVs by maintaining a separate data link, represented by arrow lines, between each UAV and the ground station. Over the data links, the vehicles are controlled through way point navigation, vehicle control, and sensor management for each UAV. Most notably, UAVs communicate only to the ground station, and not to the other UAVs.

The central challenge in the current model is that the operator must set the behavior for each UAV while simultaneously worrying about the overall deconfliction and cohesion of the vehicles in flight. That is to say, to enable multiple UAV operations, the operator must essentially enforce various rules for the UAVs that could be more simply accomplished through an emergence based flocking model, called the Ideal Model, and presented in Figure 1.2.

The problem facing the operator in this model is that each UAV requires the same amount of information to operate it. Thus, as one more UAV is added to the group of UAVs in flight, the amount of information required for the operator to control those UAVs linearly increases. With the additional challenge of deconflicting the flight patterns of the group of UAVs, the Total Information that the operator must operate with increases at an exponential rate as more vehicles are added.

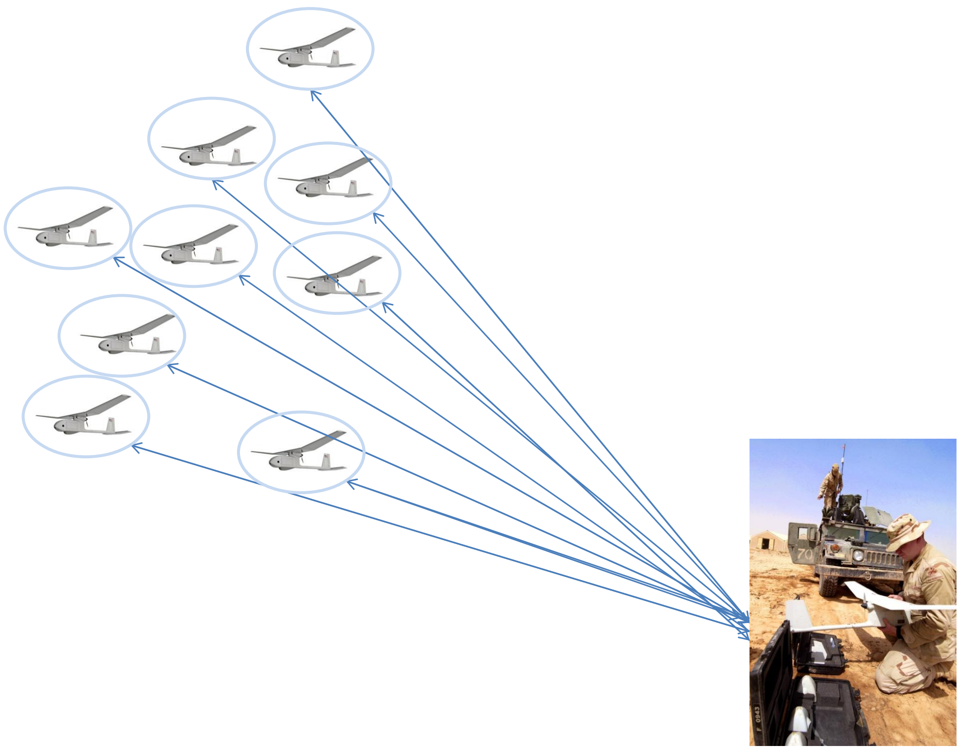

Figure 1.1: Current Model: Single Operator Directly Managing Multiple UAVs

1.2.2 Ideal Model. The Ideal Model is a solution to the challenges faced in the Current Model. In this model, the rules of emergence based flocking are applied (see Section 2.3 for details). The rules, with their associated weighting schemes vetted and developed as necessary for different segments of the mission path (Section: 3.4.1), allow the UAVs operating together in a group size of one to many vehicles, to fly as a UAV flock with minimal operator management. In fact, this model reduces the complexity to such a level that the operator would effectively be controlling the entire group of UAVs as if they were a single UAV (a list of multiple UAV missions is found in Section 3.1).

The communications and information processing structure can be implemented in different ways, but in terms of management complexity, the operator need only communicate with the flock as a whole and vice versa (See Assumptions in Section 3.5.2 for what this entails). This Ideal Model is depicted in Figure 1.2 which shows a group of UAVs mid-flight, where the UAVs are communicating with each other and the entirety of the group is communicating with the operator.

As compared to the Current Model, the addition of one UAV to the group of UAVs or UAV flock under the Ideal Model does not increase the complexity of managing the flock for the operator because the operator controls the flock by effectively managing only the centroid of the UAV flock. This will be explained in more detail in subsequent chapters.

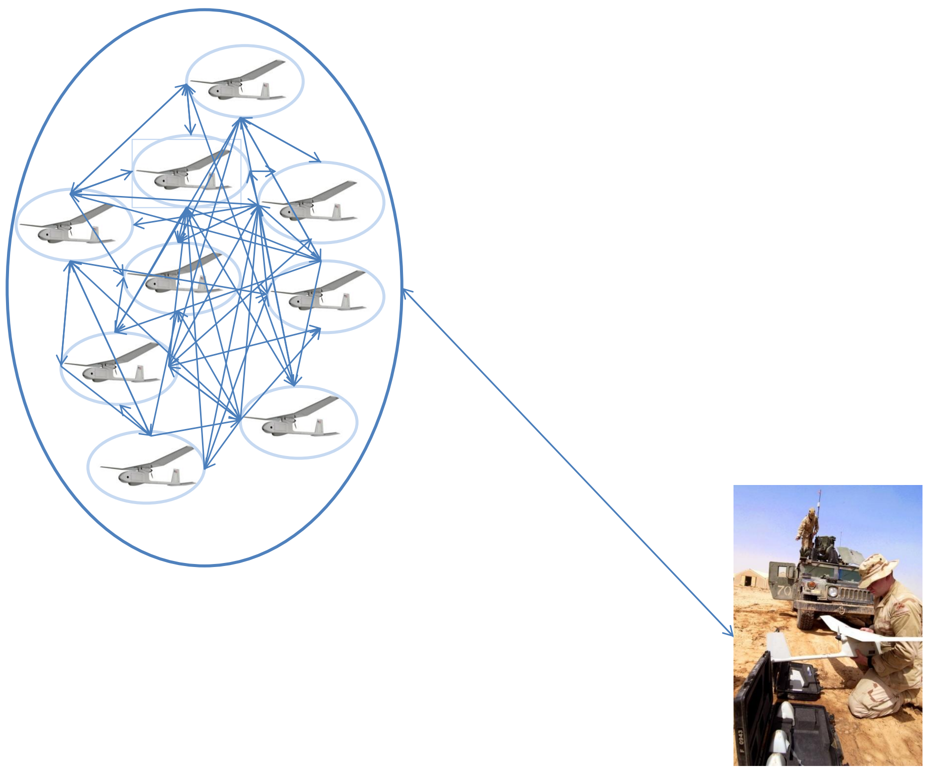

Figure 1.2: Ideal Model: Single Operator Managing UAV flock As One UAV

1.3 Scope and Assumptions

The solution to min(O/V) presented in this thesis is meant to be system independent. As a result, all levels of complexity of UAVs and their corresponding wide array of operational setups are by definition included. The proposed solution is resilient to such wide arrays because only the common elements of rules and information are considered; both of which can be readily adapted to different implementations. The OWL system will be featured prominently in the role of application exemplar, yet the OWL system implementation is just one of many possible single operator multiple UAV implementations. For ease of discussion, the more and less complex UAVs are considered essentially the same. That is to say, from the time UAVs are launched into the air to when they touch the ground, every UAV, despite variances in complexity, is relatively similar; nearly all UAVs have some type of payload such as a camera, some type of thrust to generate lift, etc.

The best solution to min(O/V) would involve a fully autonomous flock of UAVs because there would be no need for human operators. However, due to legal challenges, logistical hurdles, and the current low reliability of systems, such a solution is far in the future. Operators are currently required to always maintain some level of control over the system. In the most reduced method of control currently acceptable, the operator may only need to communicate the mission details to the UAV and then, if there is no weapons deployment, no longer engage with the UAV until the mission is complete as measured by some preset criteria.

The large scope of this paper and depth of each respective chapter implies that some areas will not be covered in as much detail as desired. These sections are thus presented as essential elements of the solution to min(O/V) but will be left as future areas of research.

1.4 Research Purpose

There are extensive benefits to solving min(O/V). As researchers working at and with the Air Force Research Laboratory wrote, "current techniques of controlling UAVs, which rely on centralized control and on the availability of global information, are not

suited to the control of UAV swarms" (Gaudiano *et al.*, 2003). Without a different approach, increasing the number of UAVs beyond a very low threshold, will overtax the operator. In fact, a parallel challenge exists in considering that the USAF does not typically fly manned combat missions in numbers greater than two or four due to the issues listed below from the 2004 Sandia Report (Feddema *et al.*, 2004):

1. Increased probability of detection (wider RADAR cross-section). Surprise is nine-tenths of air combat success.
2. Divided attention of pilot to keep track of wingmen.
3. Formation tactics usually result in reduced aircraft performance.
4. Increased communication (problems with attendant task loading and greater probability of electronic detection).

The same is true of UAVs under the Current Model where the term "operator" can be substituted for "pilot". Like a pilot, a human operator has a limited ability to process information of the UAVs. To achieve operator direction of groups of UAVs, these challenges need to be addressed.

Through reducing the workload of the operator, that operator becomes free to do other things, or to perform the assigned mission that much better. This would be especially true for a single operator in the field operating a set of small UAVs. For example, while the vehicles were transitioning to their target and performing their mission nearly autonomously, the operator could maintain his or her safety from enemy units.

This thesis is intended provide a solution to min(O/V) by addressing the problems inherent in the Current Model through the presentation of an Ideal Model. The benefits of the Ideal Model will be analyzed from the standpoint of information management. In summary, the objective of this thesis is to present insight into the engineering of single operator, multiple UAV architectures.

1.5 Summary Statement

The goal of this thesis is to present a solution to the problem of min(O/V) by outlining a methodology to move from the Current Model to the Ideal Model and de-

fending the benefits through analyzing and comparing the information requirements of both models. This will be accomplished by focusing on three different components. First, a literature review, example construction, and analysis of an emergence based flocking simulation will be conducted to demonstrate the potential for application to UAVs. Secondly, a robust example of a General Information Model for a single operator managing a group of UAVs will be constructed. Finally, the Current and Ideal Information Models will be broken out as subsets of the General Information Model. These models will then be used to find the total amount of information needed over the course of a sample mission and the comparison will show the benefit in employing the Ideal Model over the Current Model when more than one UAV is needed.

II. Flocking

Flocking behavior is an autonomic response that some bird species exhibit during flight. Biological research shows that complex clustering behavior during flight appears to emerge from a set of simple principles or rules with which each individual bird operates. Some important examples from Craig Reynolds (1987) paper include: maintaining distance from neighbors (Separation, or rule 1), steering toward the average long range position of the flock (Alignment, or rule 2), and steering toward the average heading of the flock (Cohesion, or rule 3). While these rules and their interaction structure forms a reasonable flocking simulation, more is needed for application to UAVs because unlike the natural world, an operator is integral to the operation of the flock.

UAV flocks will always remain under some level of operator control. Even with this control, UAV flocks should still exhibit flocking behavior because operator designed missions for UAV flocks have clear analogies in biology. For example, the additional rules needed to apply a flock simulation to a group of UAVs includes: a rule restricting the movement of the UAVs based on communication range (rule 4), travel to a point or migration (rule 5), repel from a point as if from a predator (rule 6), and travel to and operation within a goal area such as when feeding (rule 7). Like birds, UAVs have some practical limitations to their operation, some of which include: a minimum velocity for non-hovering UAVs (practical constraint 1), a maximum velocity (practical constraint 2), and a turn speed maximum (practical constraint 3).

As an outline, this chapter will begin by describing some of the research performed to develop flocking simulations and some of the issues that need to be addressed for application to a UAV flock. Next, the rules needed for a UAV flock and a specific simulation implementation developed for this thesis is presented. Some of the challenges that arose in the construction of the simulation will be discussed along with future recommendations for flocking simulations. Finally, the corresponding information requirements for the simulation will be noted for further analysis in the subsequent chapter (Chapter III).

2.1 Background

The concept of flocking has existed for many years and has associated with it a wide array of conjecture. As such, this section seeks to provide salient background information for understanding the flocking behavior that is proposed for application to UAVs.

2.1.1 Definition of Flocking. Flock behavior is a complex behavior. Individuals have developed many different definitions in order to summarize the behavior within the term flocking. For example, the compact edition of the 1971 Oxford English dictionary defines flocking as "a number of animals of one kind, feeding or traveling in company. Now chiefly applied to an assemblage of birds (esp. geese) or of sheep or goats; in other applications [it is] commonly [referred to as] herd, swarm, etc." (Oxford University Press, 1971). While time has passed, the definitions have not grown much more complex. Of the modern research community, Craig W. Reynolds defines flocking as referring "generically to a group of objects that exhibit the general class of polarized, non colliding, aggregate motion." The term polarization is from zoology meaning alignment of animal group. These definitions vary slightly but share the same essential elements. For the sake of this thesis, flocking will be operationally defined as: a homogeneous collection of flying entities that operate as a group through styles of defense, movement, etc.

2.1.2 Adaptation from Nature. In the natural world, animals group together to accomplish goals that individuals could not accomplish alone. Despite the extraordinary strength of an individual ant, ants can only support the colony when all of the individuals work together, or swarm, to find food, build the nest, and perform other vital functions. Herds of grazing animals such as elephants in the plains of Africa will stay close together so that when a predator threatens the herd, the adults will form a circle protecting the weaker members from the predator. When birds flock in the air, the swirling mass allows them to better avoid predators and their density will likely cause injury upon a predator's dive into the flock.

Figure 2.1: Defensive Formation of Musk Ox Found in Nature (Harun Yahya International, 2010)

Figure 2.2: Defensive Formation Adapted from the Natural World (Thompson, 1875)

Throughout the course of time, humans have either mimicked the natural world or, more recently, willfully applied it in their technological endeavors. In the early Paleolithic period, homosapiens would band together to kill much large animals such as mammoths. During the 1800's, Britain would form infantry squares in order to provide an organized defense against cavalry attacks.

Adapting powerful biological tools from nature has a long history, from the low tech adoptions described above to advanced technology applications. With the advent

of computer chip miniaturization, advanced computer processing, and well understood UAVs, among other developments, humans can now adapt flocking behavior from nature. The first step is to understand the behavior of bird flocks well enough to develop a computer simulation.

2.1.3 History of Flocking Simulations. Applying a novel biological concept to technology, known as biologically-inspired technology, requires a truly multidisciplinary approach. In a simplified development path, there are four general steps required before a biologically-inspired system can be demonstrated. First, the biological phenomena itself must be documented as a specific and recurring phenomena. Second, specialists must collect as much data as possible from different sources in the field. Third, specialists, mathematicians, physicists, statisticians and other individuals from related fields may study the data and possibly develop simulations and theories based on the data. Fourth, engineers take the theoretical ideas and develop actual systems. Each progression must be made only on a sound basis of the step before. Flocking behavior represents one such novel biological concept that is increasingly viewed as a potentially powerful behavior to understand and apply to technology.

Aerial formations of birds have interested casual observers for at least as long as early written history. As Iztok Bajec describes in “Organized Flight in Birds”, Pliny the Elder wrote of geese flying in formations, ‘like fast galleys’ (Bajec and Heppner, 2009). Beyond individual analysis, according to Bajac (2009), in depth questioning of flocking behavior did not begin until the early 1900’s. At this point many ornithologists began to report on measurements taken in the field. One such prominent researcher by the name of Edmund Selous, having observed flocks for thirty years, concluded that flocks of birds operate together through an inexplicable, near instantaneous link to each other. In fact, he proposed that the birds were operating through thought transference or telepathy. As a commonly understood and now well documented phenomena, flocking confounded observers until the late 1970’s (Bajec and Heppner, 2009).

With extensive field data collected, researchers began to take serious interest in explaining the organizing methodologies of flocking. Two notable paths were pursued. The

first is represented by Frank Heppner's work in simulating a flock through the mathematics of nonlinear dynamics during the late 1980's (Bajec *et al.*, 2005). Simultaneously, although in the field of computer graphics, Craig Reynolds developed a model of flocking reliant on a few key rules applied to each individual member of the flock in order to obtain a group dynamic similar to true flocks (Reynolds, 1987). Both models have various advantages, but in general, Reynolds model has stood as the basis of extensive development due to its dual simplicity of execution with seemingly accurate flock representation.

In the last few years, interest in flocking has greatly increased as research, hardware, and software has progressed far enough that actual applications are possible, especially in the burgeoning field of UAVs. New research seeks to apply the more mature field of particle physics to flocks of birds, improved imaging techniques have revolutionized field research and analysis of starling flocks (Olfati-Saber, 2004), and software developers are increasingly studying potential applications.

2.1.4 Bird Formations. Frank Heppner, a long time ornithologist, developed a taxonomy for bird formations in 1974 by introducing the terms "flight aggregation" and "flight flock" (Bajec and Heppner, 2009). Flight aggregation is defined by "a group of flying birds, lacking coordination in turning, spacing, velocity, flight direction of individual birds" (Bajec *et al.*, 2005). Flight flock is defined by "a group of flying birds, coordinated in one or more of the following parameters of flight: turning, spacing, velocity, and flight direction of individual birds" (Bajec *et al.*, 2005). There are two types of flight formations, line formation and cluster formation. Line formations mostly consist of relatively large birds such as geese forming into columns, echelons, V and J shaped arrangements, and a single front (see Figure 2.3). Cluster formations generally occur with smaller birds such as starlings, and are represented as a front cluster, globular cluster, or extended cluster (see Figure 2.4). It is important to note that both sets of patterns are approximate flying formations, not the exact formations that the respective size birds will always take (Bajec *et al.*, 2005). For example, line flying birds such as geese may sometimes be seen in a cluster formation. The relative advantages of line formations and

cluster formations have been theorized (see Dimock and Selig (2003) for more details), but nothing has been definitively proved.

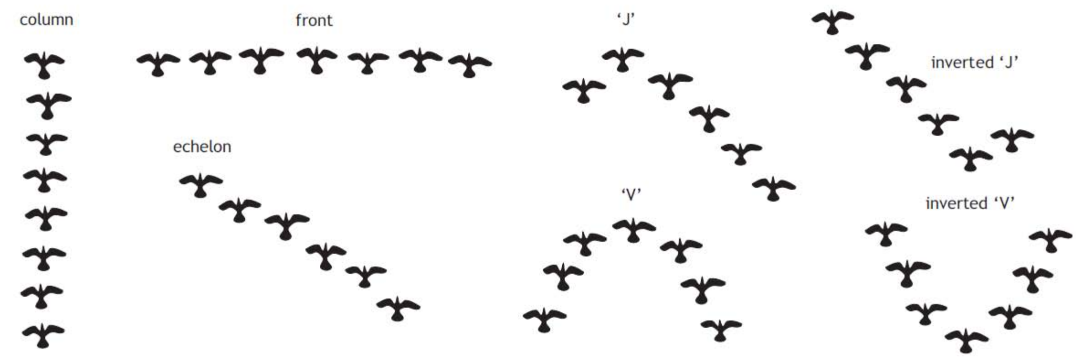

Figure 2.3: Bird Line Formations (Bajec *et al.*, 2005)

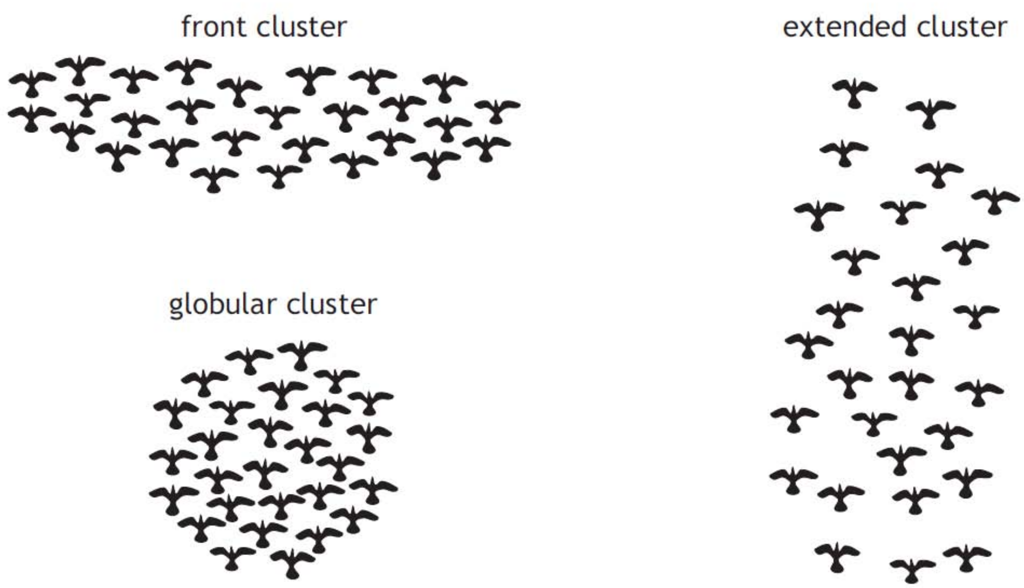

Figure 2.4: Bird Clustering Formations (Bajec *et al.*, 2005)

2.2 Mechanics of Flocking

As late as the early twentieth century, some ornithologists believed that the flocks operated by birds communicating their thoughts telepathically (Bajec and Heppner, 2009). While it is impossible to fully understand beyond any reasonable doubt how birds

flock, many researchers, including Reynolds (1987), Heppner and Grenander (2009), and a plethora of more modern algorithmic development and researchers (Bajec and Heppner, 2009), believe that emergent behavior guides the interaction of birds such that flocking can occur. In order to test the theory in a simulated environment, researchers proposed rules to capture the essential behavior of a bird at the local structure so that flocking behavior emerged in the global structure. Craig W. Reynolds proposed the first rule-based model in (1987) while he was working as a computer graphics engineer. Other methods have been pursued, such as the work of Okubo in 1986 and more recently, physicists creating flocking behavior based on work completed for particle physics. See Bajec and Heppner (2009) for a thorough discussion of the development of flocking simulations. The majority of researchers have furthered the work of Reynolds based rule model in order to simulate flocking.

A potential issue in attempting to simulate biological flocking behavior stems from the fact that a simulation will never be able to exactly mimic the natural behavior in a real world environment due to the innumerable and unknown variables. Even if researchers were able to fully understand all aspects of how birds flock, which they do not as of now, directly translating all aspects of the behavior into a simulation would not be possible. Therefore, it is incumbent upon researchers to be faithful to the biological reality so as to gain the benefits, while adapting to fit the current development effort. In pursuing these efforts, a few obvious trade-offs arise in considering application to UAVs. For example, Selous conjectured in the 1930s that birds have the ability to telepathically and instantly communicate with each other. While it is highly unlikely birds communicate telepathically, UAVs could all have the same 'thought' either at the exact same moment through similarity of programming, or nearly instantaneously through rapid communications. It stands as unnecessary to literally translate understood behavior, but rather to adapt it thoroughly enough so that designers could make trade-offs in the eventual implementation, and operators can reap the rewards of the biological phenomena.

2.2.1 Emergence. Emergence has a deceptively simple definition, which dictionary.com defines as "the act or process of emerging" (Information, n.d.), yet the scientific definition of emergence from a behavioral standpoint captures a novel idea. A.J. Ryan developed a thorough defense of what he considers a scientific definition of emergence in his 2006 paper titled "Emergence is coupled to scope, not level" (Ryan, 2007). He principally breaks down the concept of emergence as the difference between a local structure and a global structure:

> Firstly, we need to say what an emergent property is. Quite simply, an emergent property is a difference between local and global structure. A simple example from topology is the Mobius strip, depicted in Figure 2.5. Locally, the Mobius strip has two sides, a front and a back. Yet globally, the Mobius strip is one sided. Because of the twist, an ant walking along the surface would traverse the 'back' and 'front' as a single surface before it returned to its starting point. The difference in local and global structure means that if an observer only looks locally, she will not see the emergent properties of a system. Therefore, an observer must have a sufficient scope of observation before she can recognize an emergent property (Ryan, 2008).

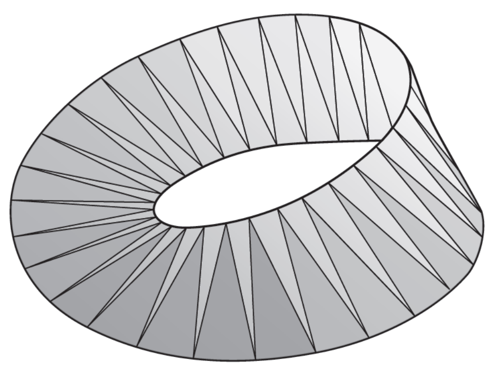

Figure 2.5: Mobius Strip (Ryan, 2008)

Ryan then provides the following definition of emergence: "Emergence is the process whereby the assembly, breakdown or restructuring of a system results in one or more novel emergent properties"(Ryan, 2008).

In seeking to apply the flocking behavior of birds to a group of UAVs, emergence based models serve as an excellent means for adaptation. One notable advantage of emergence based models is that amount of computing resources required is significantly less than that of non-emergence based models; this will be shown in the following chapter.

In general, biologically-inspired emergence based applications have some specific pros and cons. According to Kevin Kelly's book "Out of Control" (1994), some of the benefits include "adaptable, evolvable, resilient, boundless, novel" while some of the drawbacks include "non-controllable, non-predictable, non-understandable, and non-immediate". For a full explanation of the terms, please see Kelly (1994), but it will suffice to consider the terms at face value. All of the benefits are aptly suited for the employment of UAVs, such as the fact that circumstances during missions can rapidly change and specific vehicles in the UAV flock may fail during the mission. The cons appear to indicate a serious drawback. UAV flocks need to be controlled, at least in their deployment of weapons, yet emergence based systems are purported to be non-controllable. While Kelly presents this serious cause for concern in general applications, in applying emergence based rules to UAV flocks, it is relatively easy to add human control as will be seen in Section 2.3.

While it may be simple to enable human control of an autonomous UAV flock, there remains a challenge of balancing the amount of control with the emergent characteristics of the UAV flock (for more information on levels of automation please see such sources as: Ruff and S. (2002) and Cummings and Mitchell (2007)). From a purely biological standpoint, bird flocks appear to be fully autonomous. However, bird flocks can also have organized goals, such as feeding at a specific destination (Bajec and Heppner, 2009). Bird flock's goals have natural parallels for the operator's management of UAVs: a waypoint destination can be considered in the same manner as that of a destination for feeding. Stringing together a series of waypoints creates a path for the UAV flock to follow. These goals provide a clear methodology to maintain emergence while applying some amount of control over the flock.

2.3 Model Description and Simulation

Emergence based models can be implemented in a variety of different ways. While this thesis focuses on one particular implementation, the rules presented in full detail in the following subsections, represent a core set of rules that will likely be essential to any future implementation of emergence based flocking models to UAVs. The first three

rules were selected based on Reynolds' early work (1987), as are most modern models of flocking (Bajec and Heppner, 2009). Rules four through seven are deemed necessary for application to the Current Model in order to move to the Ideal Model. As will be clearly described in Section 3.2, the scenario that the operator will lead the UAV flock through is that of a simple reconnaissance mission in which a few practical considerations are added as constraints.

In order to support the validity of the core set of rules, a UAV flock simulation was developed for this thesis in MATLAB. Inspired in small part by Michael LaLena's flocking simulation (2006), the UAV flock simulation encodes the rules and constraints mentioned above. The overall integration of the rules into a constrained velocity vector will first be presented, followed by a verbal description and example implementation of each rule in the UAV flock simulation.

2.3.1 Cummulative Rules for UAV flock Movement. The behavior of a UAV within a flock can be principally understood as self-directed movements over time. That is to say, at some time t, a UAV may need to move closer to other UAVs, repel away, change heading toward a target or waypoint, return toward home base, etc. All of the rules seek to provide structure to this at a local level so that the global behavior of a flock is realized.

Thus, let F be a set of N UAVs each defined by a position vector $\vec{p_i}(t)$ and velocity vector $\vec{v_i}(t), i \in F$. At each discrete time t in the simulation (animation), each UAV's velocity vector is changed according to a set of flocking rules, which can be constrained to various levels of aerodynamic fidelity. To that end, a baseline approach uses a weighted sum of flocking rules. Each rule provides a velocity change vector $\Delta\vec{v}$. Therefore the velocity at the next time step for the i^{th} UAV is

$$\vec{v_i}(t + \Delta t) = \vec{v_i}(t) + \sum_{r=1}^{7} w_r \Delta\vec{v_r} \tag{2.1}$$

where $\vec{v_i}(t)$ and $\vec{v_i}(t+\Delta t)$ are the velocity vectors of the i^{th} UAV at given times

w_r is the weight for the r^{th} rule, and

$\Delta\vec{v_r}$ is the velocity change from the r^{th} rule (for the of i^{th} UAV).

Reynolds also examined an alternate approach using an "accumulator" to prioritize the set of flocking rules into the overall change (1987). Regardless of of the method of rule aggregation strategy, the UAV then moves over time by re-evaluating the summation and adjusting its velocity and position every time step. The new position is simply

$$\vec{p_i}(t+\Delta t) = \vec{p_i}(t) + \Delta\vec{v_i}(t)\Delta t \tag{2.2}$$

In addition to the rules, some practical limitations or constraints for the UAV must also be considered. With the overall summation defined, it is next necessary to elaborate on each individual rule.

2.3.2 Rule 1 ($\Delta\vec{v_1}$): Separation. Jonathan Gabbai (2005) described this rule as "steering to avoid crowding of local flock-mates". Some authors have referred to this behavior as collision avoidance, though it is focused on collision with other flock members, not external objects. In terms of UAVs, this separation represents a safe distance that a UAV must maintain between itself and other local UAVs in the flock. The change in velocity contributed by this first rule is derived from the average distance away from the neighboring UAVs around the i^{th} UAV. Let d_s represent a predetermined separation distance d_s between UAVs. This distance imparts a space centered at the position of the i^{th} UAV with radius, d_s. Any UAVs in this space are considered in the neighborhood set N_{i,d_s} of the i^{th} UAV. The basic rule is as follows.

$$\Delta\vec{v_1} = \frac{\sum_{j\in N_{i,d_s}}(\vec{p_i}-\vec{p_j})}{|N_{i,d_s}|\Delta t}, i \neq j \tag{2.3}$$

where $|N_{i,d_s}|$ is the size of the neighborhood around the i^{th} UAV.

This rule is necessary in so far as current UAVs must maintain a safe distance around themselves to operate. Thus, d_s is based on a need to maintain lift, move independently, and make sudden course adjustments, among other salient factors. Addi-

tionally, d_s could be based on a safe multiple of wing-span. This rule can be combined with a penalty function to further promote or emphasize collision avoidance which an be adjusted to increase the change in velocity for close neighbors. Generally, as the distance between neighboring UAVs becomes close, the repulsion drive between the UAVs increases to a maximum.

$$\Delta\vec{v_1} = \frac{\sum_{j \in N_{i,d_s}} C_{ij}(\vec{p_i} - \vec{p_j})}{|N_{i,d_s}||\vec{p_i} - \vec{p_j}|\Delta t}, i \neq j$$

where $C_{ij} = \begin{cases} C(1 - |(\vec{p_i} - \vec{p_j})|d_s)^2, & |\vec{p_i} - \vec{p_j}| < d_s; \\ 0, & |\vec{p_i} - \vec{p_j}| \geq d_s. \end{cases}$

The constant C can be any valid velocity magnitude (speed). Naturally other functions could be used. Also, C could be dynamically altered throughout a mission. This ability to change the behavior or variations of the flocking rules will be addressed as a required information flow.

2.3.3 Rule 2 ($\Delta\vec{v_2}$): Alignment. Gabbai (2005) describes this rule as "steering toward the average heading of local flock mates". For UAVs, this rule matches the velocity of one UAV with that of its neighbors. Based on recent research, birds perform actions such as local heading and the following rule of cohesion based upon the actions of the six or seven closest neighbors as measured from the centers of mass of each UAV (Cavagna *et al.*, 2008). While this may be true for birds, UAVs' communication abilities allow for various different implementations of this rule. While, a fixed number of closest neighbors could be used for alignment, a similar approach to Rule 1 will be used, based on a neighborhood set N_{i,d_a} parameterized by a distance d_a. This could be related to communications or sensor capabilities. Rule 2 allows small groups ("flockettes") to merge, and allows UAVs on the edges of the flock to not move away from the flock center.

Averaging local velocities, the change to the the i^{th} UAV then (Gabbai, 2005):

$$\Delta\vec{v_2} = \frac{1}{|N_{i,d_a}|} \sum_{j \in N_{i,d_a}} \vec{v_j}, i \neq j$$

2.3.4 Rule 3 ($\Delta\vec{v_3}$): Cohesion. Gabbai (2005) defines this rule as "steer to move toward the the average position of local flock-mates". This rule is also referred to as flock centering. UAVs will use this rule to calculate the center of mass of the local flock and nominally head to that position. This maintains the cohesion of the entire flock.

Similarly as above, there is a preset cohesion distance d_c which establishes the size of the Neighborhood N_{i,d_c} around the i^{th} UAV. Rule 3 averages the neighbor positions to find the centroid of the local flock and head to it.

$$\Delta\vec{v_3} = \frac{\sum_{j \in N_{i,d_c}} \vec{p_j}}{|N_{i,d_c}|\Delta t} - \frac{\vec{p_i}}{\Delta t}, i \neq j$$

The i^{th} UAV will take this center of mass point as its new heading, relative to its current position.

2.3.5 Rule 4 ($\vec{v_4}$): Communication Range. Every UAV has a limited communication range between itself and the ground station transmitter. At least one member of the flock must maintain contact with the home base location so that the UAV can relay any updated instructions over the course of a mission to the other members of the Flock. It is generally simpler to apply the rule by making sure all UAVs stay within transmission range of the ground station.

For example, the transmission range could simply be a circular distance from the home base, as most transmitters in the field have an approximately omni-directional pattern. Define the maximum communication radial distance as d_{mc}. Then the area that the UAV may operate within to maintain communication with the ground station is simply the area of the circle around that ground station transmitter: $\pi(d_{mc})^2$. At some fraction of this distance (say 95%) of d_{mc} away from the ground station transmitter, the UAV needs to perform a turning maneuver. The exact behavior has a number of variations, which includes: 1) heading back towards home base, 2) reflect off the virtual d_{mc} boundary, or return in the same direction (180 °). This turning maneuver for the i^{th}

UAV, if heading away from home base, is represented by:

$$\Delta\vec{v_4} = \begin{cases} -\vec{v}_i, & \vec{p_i} \geq .95 d_{mc}; \\ 0 & \vec{p_i} < .95 d_{mc}. \end{cases}$$

2.3.6 Rule 5 ($\Delta\vec{v_5}$): Migration to a Target. The primary form of control the operator has over the UAVs is through setting waypoints and/or target points. This is essential for setting targets that the UAV is to engage with, or in developing a mission path that the UAV should survey. Depending on the level of automation, the waypoints may be set by either the operator or the UAV flock, but the target will assumed to be always determined by an operator.

For example, the operator might send the UAV a coordinate position for the target T defined as $\vec{p_T}$. Once this target is assigned, each UAV in the Flock will turn toward the target and travel to it, with an optional parameter (behavior) that reflects urgency with which to proceed. Thus,

$$\Delta\vec{v_5} = \frac{\vec{p_T} - \vec{p_i}}{\Delta t} \tag{2.4}$$

Another behavior that may be communicated to the flock is intended action at the target. These could take the form of instructing the flock to spread out and find other targets, circle a known target (building), or fly patterns keeping the front camera on target.

2.3.7 Rule 6 ($\Delta\vec{v_6}$): Repel from Target. There are many instances when an individual UAV will need to be repelled from something. Rule 1 described how UAVs are repelled away from each other. Some example situations include when UAVs may need to repel from targets that are dangerous, observe a target with a side mounted camera while the UAV is in an orbit, or avoid a dangerous ground target. The biological analogue for this rule is that of predator avoidance, where the more dangerous a predator, the higher weight on repelling.

For example, define a UAV i with position $\vec{p_i}$ and target T with a position $\vec{p_T}$. One implementation of repulsion is to push the UAV on a new course circling around

the target by following the tangent of a circle of radius d_{sensor} around the target point. This range, d_{sensor}, is based on operational tactics and optimal sensor range. Generally for the AFIT OWL platform, a counterclockwise surveillance pattern will keep the left pointing camera on the target. This research also assumed that getting too close to a target (less than sensor range) was not desired.

$$\Delta\vec{v_6} = \begin{cases} \frac{C(\vec{p_T}-\vec{p_i})}{\Delta t}, & \vec{p_T} - \vec{p_i} < k_1 \cdot d_{sensor}; \\ 0 & \vec{p_T} - \vec{p_i} \geq k_2 \cdot d_{sensor}; \\ \frac{C \arctan(\vec{p_T}-\vec{p_i})+\pi/2}{\Delta t} & k_1 \cdot d_{sensor} < |\vec{p_T} - \vec{p_i}| \leq k_2 \cdot d_{sensor}. \end{cases}$$

where $k_1 \leq k_2$ define a valid range from target to loiter and C is some constant.

2.3.8 Rule 7 ($\Delta\vec{v_7}$): Goal Area. As will be further elaborated in the following chapter, each mission will be considered as a whole composed of discrete segments: take off, travel to a goal area, operation within a goal area, travel to home base, and land. The 6 rules above largely define the traveling components. This rule seeks to define the bounded goal area that the UAVs will operate within. For highly detailed implementations, this mission segment would consist of a bounded region in which UAV flock(s) perform wide area search (Jacques, 2003), joint attack (Feddema *et al.*, 2004), and other useful missions (see Section 3.1 for more details on missions for UAV flock(s)). Developing the capability to execute such maneuvers in a high quality manner requires a significant investment, but UAV flock(s) can be easily developed to accomplish reasonably difficult and appropriate missions. As a simple point, it might be possible to achieve wide area search by increasing the separation distance for each UAV in the flock while making sure the flock stays within the goal area. While the detailed programming of the goal state is beyond the scope of this thesis, the bounded goal area was developed.

As an example implementation of a goal area, let the goal area be a rectangle defined by 2 pairs of Euclidean coordinates, denoted by the opposite corners. These are represented by $\vec{p_{BL}}$ and $\vec{p_{TR}}$. Naturally, these reflect latitude and longitude, with a minimum and maximum elevation an option. Now, if the UAV is outside the boundary area, then like rule 5, the UAV i will migrate to the center of the goal area rectangle,

$(\vec{p_{BL}} + \vec{p_{TR}})/2$ which is itself treated as a point target. If UAV i is within the boundary area, then there is no effect.

$$\Delta\vec{v_7} = \begin{cases} \frac{((\vec{p_{BL}}+\vec{p_{TR}})/2)-\vec{p_i}}{\Delta t}, & \text{if } \vec{p_i} < \vec{p_{BL}} \text{ or } \vec{p_i} > \vec{p_{TR}}; \\ 0 & \text{if } \vec{p_i} \geq \vec{p_{BL}} \text{ or } \vec{p_i} \leq \vec{p_{TR}}. \end{cases}$$

2.3.9 Practical Constraint 1 ($\vec{v_{min}}$): Velocity Minimum. All vehicles that are not capable of hovering must maintain some non-zero velocity. This velocity lower bound applies to the cumulative rule for UAV flock movement in that every UAV in the flock must keep moving. Thus,

$$\vec{v_{min}} \leq \vec{v_i} \tag{2.5}$$

2.3.10 Practical Constraint 2 ($\vec{v_{max}}$): Velocity Maximum. All vehicles have a velocity that is either impossible or impractical to exceed. This represents the upper bound in velocity for the cumulative rule for UAV flock movement. Thus,

$$\vec{v_i} \leq \vec{v_{max}} \tag{2.6}$$

2.3.11 Practical Constraint 3 ($\max \Delta\vec{v}$): Turn Rate Limitation. Another limitation which affects non-hovering aerial vehicles is that of turn speed. A UAV of this type may proceed through a turn at predetermined rate. This can be represented as any angular measurement per unit time. For the AFIT OWL aircraft, for example, this limitation is about $15 \deg/sec$. Thus, for the i^{th} UAV, after all the rules are weighted and summed, this constraint, $\max \Delta\vec{v}$ is checked.

$$\vec{v_i}(t + \Delta t) = \begin{cases} \vec{v_i}(t + \Delta t), & \text{if } \sum_{r=1}^{7} w_r \Delta\vec{v_r} < \max \Delta\vec{v}; \\ \max \Delta\vec{v} & \text{otherwise.} \end{cases}$$

2.3.12 Simulation Interface. The MATLAB simulation developed for this thesis was principally used to illustrate the feasibility of the rules and constraints and illustrate a potential method for encoding. The actual simulation also developed a Graphical User

Interface (GUI) with which to both qualitatively and quantitatively evaluate the simulation as it progressed over time. Figure 2.6 is the result of that development effort for one particular simulation setup in which the UAVs are bounded within a communications region and are traveling to a target. Rule 7 has a weight of zero in this example screen shot as there is no goal area, only a target.

Various measurements provide some suggested metrics with which to evaluate the success of the flocking rules and are presented in the bottom left corner of Figure 2.6. They are defined in the following manner:

1. Mission Time: How long since start of Mission
2. Hits: UAV j and UAV i are within a small radius of each other, i.e. the vehicles collided. This simulation considered a hit radius distance as three times the length of the UAV's wingspan.
3. Near Misses: UAV j and UAV i are close to hitting each other. This simulation considered a near miss radius distance as 20 times the length of the UAV i's wingspan.
4. Average Speed in Miles Per Hour (Avg Speed): the speed measurement as an average of all members of the flock at that time.
5. Number Beyond Range: a tally of the UAVs that have gone outside the short range.
6. Number at Target: how many UAVs are within the target radius.
7. Time All at Target: the time when the entire flock reached the target (within the sensor radius).
8. Target pop up Time: the time step at which the target was assigned.
9. Flock Area: the average size of the flock using a minimum bounding box.
10. Flock Perimeter: the summation of all distances between UAVs.
11. Number In Target Area: the number of UAVs in the rectangular goal area.
12. Time All In Target Area: the time when the entire Flock reached the rectangular goal area.

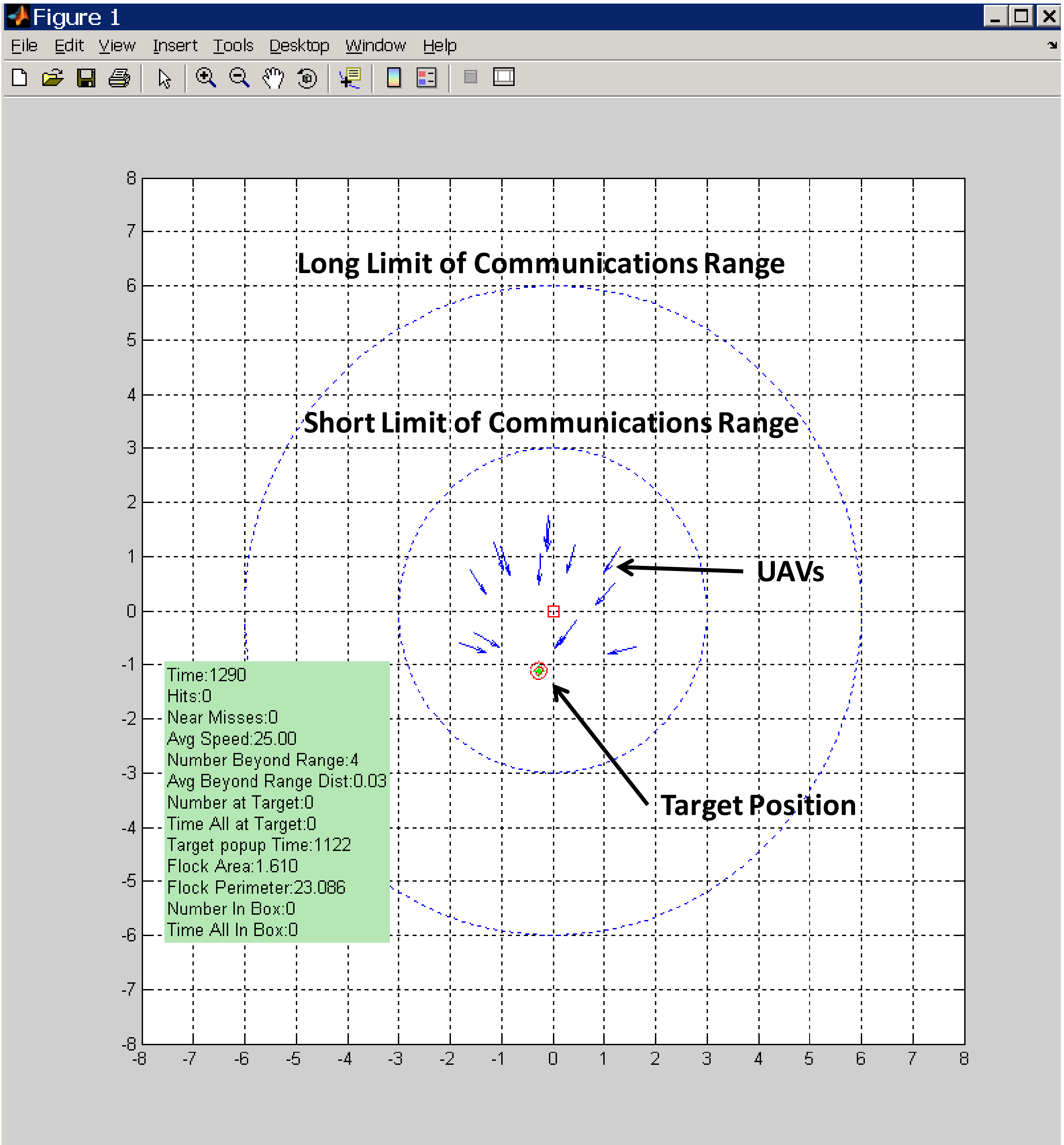

Figure 2.6: MATLAB Flock Simulation

2.4 Simulation Observations

Clearly, the list of rules and constraints provided above do not cover all scenarios and requirements that would be needed for a flocking model to be applied to a group of UAVs in order to generate flocking behavior. That said, the core set of rules and constraints provides a working baseline for how to proceed with a full implementation. The basic rules can be expanded upon to more aptly address real world mission conditions. This is especially true for the clearly simplified goal area rule. Furthermore, the constraints provide only a small amount of the detail which ties the simulation to actual UAVs but point to the value of such constraints.

The flocking simulation proved a valuable method with which to demonstrate the feasibility of the rules and their interactions. Some challenges that were uncovered over the course of the development and some future recommendations include:

1. Developing effective weights to balance out the competing rules is especially challenging and will serve as the primary obstacle to overcome in adapting emergence based modeling to UAVs. Trial and error testing or evolutionary algorithms have been proposed as reasonable methods to optimize the weighting, but such testing presents challenges in making the flock robust to all situations.
2. Goal Area or Goal State parameters need to be developed. This statement includes all of the potential missions that the UAV flock might be required to perform. Simple solutions that adapt the rules rather than add whole new sets of behavior are possible, but remain to be well implemented.
3. Most flocking simulations are developed in 2D versions with scattered and likely proprietary 3D versions. However, fully developed 3D simulations exist for UAVs under the Current Model. Melding these two types of simulations together is necessary before UAV flocks can become a reality.

With many development challenges in the way of nearly autonomous UAV flocks, it is reasonable to employ the flocking capability in some segments of the mission. As the MATLAB simulation exemplified, immediately applying the flocking behavior to transition periods in the mission would greatly ease the burden of the operator. Tied

with simple missions such as observing a stationary target, the UAV flocking model could be deployed in this restricted use in relatively short order. To view a copy of the MATLAB simulation, please direct inquires to Dr. John Colombi, whose contact information is presented at the end of this thesis within the Form 298.

2.5 Operator Information Requirements

As was noted in the description of the Current Model and Ideal Model (See Section 1.2.2), when a single operator controls multiple UAVs that operator must interact with the UAVs by sending commands and receiving information. As will be shown in the next chapter, the information requirements are vastly different between the Current Model and that of the Ideal Model. These differences stem clearly from the nature of UAV flocking emergence based rules.

The Current Model requires the operator to process all of the flight information that the UAV flock handles on its own in the Ideal Model. Under the Ideal Model, the operator needs to process significantly less, which can be seen from the rules needed for the simulation above. From the flocking simulation rules, as captured in the graphical user interface, the operator would need to know the following information about the flock:

1. Description of the UAV flock - centroid, bounding shape, or size
2. Communication range of the UAV flock
3. Relevant Health and Status of the UAV flock - battery life, time to target, command confirmation

The operator would need to send the flock such commands as:

1. Waypoint or Target position (Goal Point)
2. Goal Area description - circular, rectangular
3. Flock behavior or rule variations

Though this set of information admittedly does not include all the information an actual implementation would require, the information needed to pass between the

operator and the UAV flock is noticeably simple. This is the heart of the advantage of the Ideal Model over the Current Model. The operator need simply manage the flock waypoints, provide the target position, and describe the mission goal area. In order to further understand this advantage, a more detailed information model will be analyzed in the following chapter.

III. Information Model

The previous chapter presented an emergence based flocking model as a possible solution to min(O/V). This chapter defends the importance of such an approach through showing that the information requirements for the operator to manage a group of UAVs is significantly less under the Ideal Model than the Current Model. The defense rests primarily on the information requirements of a group of UAVs over the course of a sample mission.

An Information Model is presented as a precise way to organize and discuss real world data. Currently, there are a few different methods of modeling information. One method of depiction employed in the USAF, which also covers the broader concept of resource flows, is known as the Operational Resource Flow Matrix or Operational View 3 (Headquarters, United States Air Force, 2009a). The method under consideration in this chapter is that of a set of information. Information, or data, can be stored or transmitted in many different forms. For the sake of this chapter, a general approximation for encoding information will be presented as a computer word (See Section 3.3.2). The most important characteristic of information is whether it provides insight for a particular situation. In the case of a group of UAVs operating over the course of a mission, information is essential.

The group of UAVs controlled by an operator, independent of implementation, requires a vast amount of different information elements, at different frequencies, to account for all of the information needs of various stakeholders. A robust example of this full set of information requirements is developed in what is called the General UAV Information Model (See Section 3.5). From this large set of information, two subsets representing the information needed for an operator to control a group of UAVs under the Current and Ideal Models are broken out (See Section 3.6). Once the models are presented and the number of approximate words needed over the course of a mission are summed, the models will be compared. This chapter begins with an introduction to various multiple UAV scenarios that were deemed important applications for groups of UAVs.

3.1 UAV flock Scenarios

In order to understand the information requirements of a single operator controlling a group of UAVs, it is first essential to consider the potential missions that a group of UAVs might be called upon to perform. In late 2002, the U.S. Joint Forces Command Joint Experimentation (J9) group hosted a UAV flocking or swarming conference, during which participants "discussed and ranked the missions in which swarming concepts and capabilities have the greatest potential value – operationally sound, technically feasible, and cost-effective" (Feddema *et al.*, 2004). Below are the enumerated lists that resulted from the conference as reported in the Sandia Report in 2004. The first eight are deemed the most practical and useful missions.

1. Area Intelligence/Surveillance/Reconnaissance (ISR) and Intelligence – detect, classification, identification, neutralization, and salvage.
2. Point Target ISR – continued surveillance of an important area, multi-spectral Battle Damage Assessment (BDA) with different types of sensors to tell what is going on after attack; traffic analysis.
3. Communications / Navigation / Mapping – update of Intelligence Preparation of the Battlespace; swarming supplementation of communication networks; and precision mapping of an area (surface or sub-surface).
4. Swarming Attacks
5. Defense / Protection – submarine warfare includes tagging by swarms, potential counter to swarming boats; defensive operations for surface forces (flank protection).
6. Delay / Fix / Block
7. Deception Operations – perform a deceptive attack pattern to cover an attack at another point, decoys with swarm, electronic jamming.
8. Search and Rescue (SAR) and Combat Search and Rescue – Applying swarms of Unmanned Vehicless to find and/or retrieve personnel or other assets.

The following list of missions were deemed to be special applications for UAV flocks but were not considered primary missions; undersea operations have been excluded.

1. Clandestine or lethal obstacle clearance (minefields, toxic agents, bio hazards).
2. Recovery of objects, elements, or samples (e.g. ore, soil samples) in special environments.
3. Tracking and/or tagging operations (long-term surveillance) over wide areas or with many targets (i.e., all the containers within a given port or ports within a region; ore shipments).
4. Airfield denial or aerial exclusion zones.
5. Urban operations: communications relays, surveillance, reconnaissance, tagging, and mapping.
6. Distributed, robust (graceful degradation) “phased-array” or multi-aspect sensors and/or communications.
7. Logistics (user defined quantity, on demand, point or “home” delivery).
8. Reconnaissance – detect, classification, identification, neutralization, and salvage.

Surprisingly, the USAF UAS flight plan 2009-2047 does not list a unique selection of swarming missions. The Sandia Report from 2004 suggests that the USAF generally does not view swarming as a high priority due to both the lack of missions specified for large number of vehicles in a flock within the UAV Road Map from April 2001 and from focusing on manned flight with no more than four total planes in a division for any given mission (Feddema *et al.*, 2004).

The USAF has recently developed significantly greater interest in the potential of UAV flocks. This can clearly be seen in the most recent flight plan’s eventual goal of groups of UAVs being directed by operators in the period of fiscal year 2025-47 (Headquarters, United States Air Force, 2009b). While the scenarios developed by the U.S. Joint Forces command were developed years ago, they still capture the full spectrum of operations that a UAF flock will be expected to perform.

3.2 Sample Research Scenario

In order to develop a General UAV Information Model, all of the information needed by the UAV, the UAV flock, the Operator, and any external sources would need to be detailed for all implementations across a mission of duration T. As captured in Section 3.1, the full array of operations for UAV flocks covers a plethora of potential UAV flock implementations. A robust example is presented in Section 3.5. To cover the narrowed examples that will be developed for the Current and Ideal Information Model subsets, a specific sample implementation of a vehicle, based largely on the AFIT SUAS 2010 group's OWL platform (Seibert *et al.*, 2010) will be considered. While the OWL platform is a solid representative of the Current Model, the Ideal Model's UAV will represent a theorized future implementation of the information requirements of the emergence-based flocking found in the previous chapter to the OWL vehicle. The respective models will be based on the following 90 minute sample scenario which stands as a representative of the full list of scenarios:

> A group of N homogeneous UAVs (OWL Vehicles) are launched from a home base one at a time. Once in the air, at some specified altitude, the UAVs move to a loiter point and form into a group under the Current Model or a UAV flock under the Ideal Model (via either a line or cluster formation). Consider this take-off time period $t1$ with a time length of 12 minutes. During the next mission segment, $t2$, the flock travels to the goal state over 10 minutes. Upon entering the goal area, the group of UAVs begins to perform a surveillance mission of a non-moving target for time $t3$ or 46 minutes. After t3 has elapsed, the group of UAVs travels back to the home base during time $t4$ which lasts 10 minutes. Once arriving at a loiter point, the UAVs then land one at a time and the mission is concluded when the last UAV has landed. Consider the landing time as $t5$ which takes 12 minutes.

Each mission segment is generally understood as lasting a time ti where $1 \leq i \leq 5$, but in the case of this sample scenario, each segment lasts the stated durations. While this simplified scenario leaves a significant amount of detail about the required instructions for the UAVs out of the description, most notably the potential challenges that inevitably arise over the course of an actual mission (such as an unpredictable and hostile target), it is important to note that the Information Model and subsequent operations, are provided as a general structure with which to model and understand information needed by groups

of UAVs. In the case of this thesis, it primarily serves as a means of demonstrating min(O/V).

3.3 Information Definition

The presentation of information will begin broadly. That is to say, the set of all information, independent of any particular situation or instantiation, consists of an infinite collection of elements within an information set. The expansive definition of information is:

Definition 1. *Information is something told; news; intelligence or knowledge acquired in any manner; facts; data; learning. (Agnes and Guralnik, 2002)*

Although the set of all information is infinite, the information that is important in a particular circumstance is limited and can be listed. For example, consider a subset of the set of all information that consists of the information necessary to detail television programming. One element of the set could represent the name of one television channel, the standard time slot length for a show on one channel, the most popular commercial on one channel, etc. As another example, an aircraft has a downward pointing digital, two dimensional camera that records or transmits image frames, of a particular nxm pixel dimension, at some rate throughout the flight. A partial set of data for this scenario consists of the details of the aircraft itself, such as fuel level, location and ground speed, and information about the image being stored, such as resolution quality.

All information may be stored or transmitted in a variety of ways. This thesis focuses on the narrower concept of information as defined within the context of Information Theory.

3.3.1 Information Theory Background. Information theory prescribes a measure for the amount of total information in a communication channel, commonly called Shannon's entropy. Claude Shannon, widely known as the "father of information theory" (MIT, 2001), (Alcatel-Lucent, 2006), was one of the first to consider information in a mathematically rigorous fashion. With his seminal work, "A Mathematical Theory of Communication", Shannon (1948) changed how communication was understood. Be-

fore his paper, communication devices and pathways were each unique with nearly every device maintaining a separate field of study. Shannon, relying primarily on the fields of electrical engineering and mathematics, studied the distinctly separate communication devices of the time and abstracted out a unifying concept: information (Chiu *et al.*, 2001). Through his paper and his later work, Shannon presented a coherent methodology to quantify information for transmission.

Since Shannon's paper, the field of information theory and methods of information transmission have significantly evolved, yet the basic premise remains the same. Information must be encoded in some manner, of which there are many, to transmit it through a channel. It is from this information theoretical context that data or information will be understood for the remainder of this chapter.

The information theoretical definition of information is "a precise measure of the information content of a message" (Agnes and Guralnik, 2002). In 1948, Shannon described information in the following manner:

> The choice of a logarithmic base corresponds to the choice of a unit for measuring information. If the base 2 is used the resulting units may be called binary digits, or more briefly bits, a word suggested by J. W. Tukey. A device with two stable positions, such as a relay or a flip-flop circuit, can store one bit of information. N such devices can store N bits, since the total number of possible states is 2^N and $log_2 2^N = N$ (Shannon, 1948).

The information theoretical description of a "bit" represents a unit of measurement of information stored and communicated over a communication channel. Shannon's measure is commonly referred to as the "entropy" of the signal, a real number. It also is understood by information theory practitioners to be equal to the Least Lower Bound of the average number of bits needed to encode the information in a signal. In order to transform to a common metric and provide calculation for amount of information that UAVs require to operate, this thesis uses a measure called "computer words", where a word is the number of bits manipulated by modern computer processors.

3.3.2 Computer Words. Collections of bits, interpreted as powers of 2 in the form of 2^n are grouped as computer words. Typically, modern personal computers use

32 bit or 64 bit words. For the remainder of the chapter, let W represent a generic word of variable length.

Consider the following simple examples to illustrate how a word encodes information. A character in a computer (e.g., a letter, number, symbol) is often encoded as one byte (e.g., an 8 bit word). A word can further encode an integer in a computer (e.g., a 32 bit word). As another example, consider a matrix M, of size S x T, where S and T are the number of pixels (information elements) to be encoded. If $S = 10$ and $T = 30$, then the matrix has $10 * 30 = 300$ elements. If each pixel can be one of 256 gray scale colors, then in order to encode this information, 300 8-bit words would be needed.

3.4 Instantaneous, Total Information and Information Density

The number of words in an Information Model depends heavily on the concept of time. The Information Model or the set of information S of a concept represents all information needed to fully describe that concept across its time frame, described here as an interval of time T. At any specific time $t \in T$ of S, the amount of information measured in words transmitted and/or stored at a specific time t can be identified. This concept and others that are closely related are captured in the following definitions:

Definition 2. *Suppose S is an Information Model. Define Instantaneous Information, $\sigma(t)$ as the information required for transmission between the operator and the group of UAVs at some specific time t.*

Definition 3. *Suppose S is an Information Model. Then define a scale denoted, $\sigma'(t)$ of S. This scale describes the amount of information measured in words per unit time for S at some time t and is called the Information Density of the Information Model.*

Because information is all stored in the same format of words, it is possible to sum all of the Instantaneous Information requirements over the course of the mission (T):

Definition 4. *Total Information, denoted by*

$$\sum_{t=0}^{T/\Delta t} \sigma(t)$$

is defined as the sum of Instantaneous Information over some interval of time.

Assuming quasi-stationary information characteristics over various mission segments, Total Information can be calculated as

$$\sum_{\text{segments}} \sigma'(t) T_{\text{segment}}$$

.

It is important to note that Total Information over the course of a mission depends heavily on the length of the mission segments (defined in the next subsection), and is also clearly dependent on the frequency of update, Δt. Because implementation independent models are under consideration for this thesis, the frequency of update will represented qualitatively by: none, low, medium, and high. These variables will allow for calculation of the amount of Total Information for the Current and Ideal Information Models.

3.4.1 Mission Segments. Different segments of a mission require different sets of information that remain essentially constant for the duration of that segment. These segments were first identified in the description of the Sample Scenario, and are largely applicable to many missions that a group of UAVs would be required to perform. The mission segments identified specifically for the Sample Scenario are as follows:

1. Take Off: t1, Time Length: 12 minutes
2. Transition (en route, ingress): t2, Time Length: 10 minutes
3. Goal State (during which the observation of the stationary target takes place): t3, Time Length: 46 minutes
4. Transition (return to base, egress): t4, Time Length: 10 minutes
5. Landing: t5, Time Length: 12 minutes

The Sample Scenario and the corresponding mission segments form the foundation upon which the Current Model and Ideal Model are compared because each segment are equivelent for the different models; this will be further analyzed in the Current and Ideal Instantaneous Information Models. The equivelence in terms of segment time length

and mission segment breakdown over the course of the Sample Scenario is illustrated in Figure 3.1.

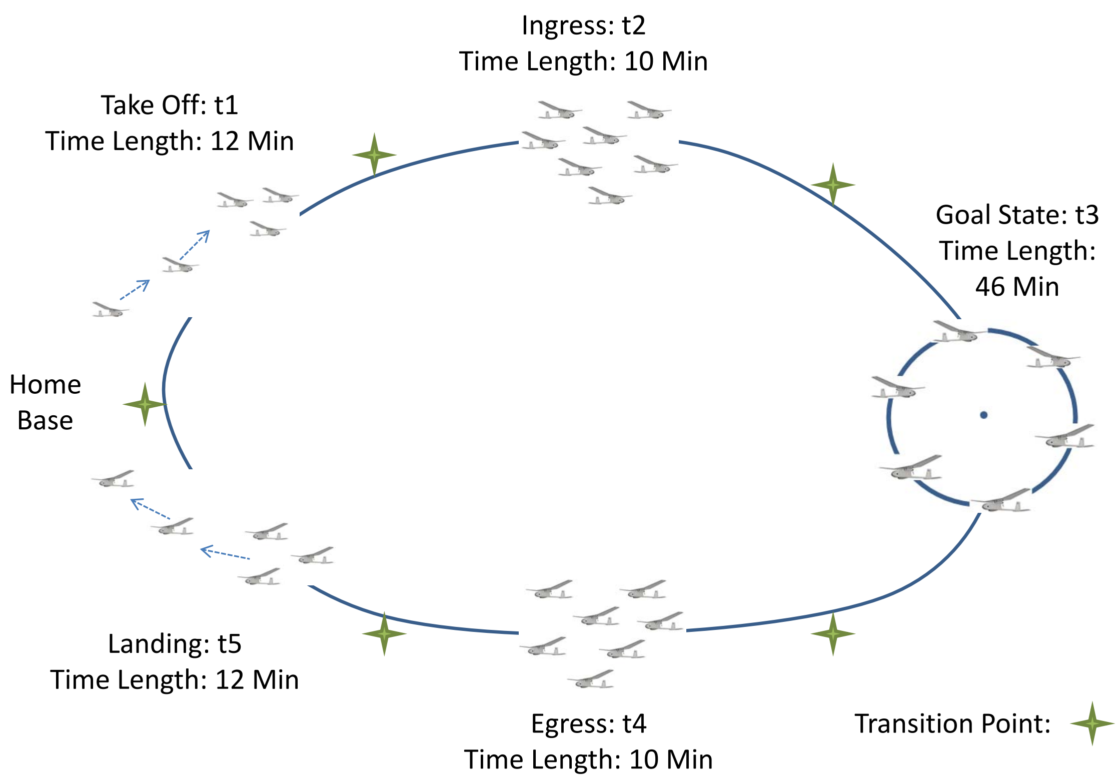

Figure 3.1: Sample Scenario by Mission Segment

3.5 General UAV Information Model

The construction of the General UAV Information Model begins with a review of the motivation. It is followed by some essential assumptions for the Information Model. Next, the categorical headers for the Information Model will be presented for ease of understanding the then self-explanatory General UAV Information Model.

3.5.1 Information Model Motivation.

The flocking model presented in the previous chapter offered a potential method for UAVs to exhibit autonomy, thereby reducing operator information requirements. That model, along with other potential solutions that successfully applies bird flocking behavior to UAVs, requires a substantial amount of communication between every UAV in the flock and between the UAV flock and the operator. Extensive communication has drawbacks, some of which include: increased chance of detection by enemies, the effect that delay on transmission has on operations, and broadcast transmission and reception requirements.

The purpose of communication both within the flock and to and from sources outside the flock is to transmit information between the sources of information and the ultimate destinations or sinks of information through a channel for use by the sinks. For example, operators need to maintain some level of control over the flock by transmitting goal states from a ground station (source) to the UAV flock (sink). Operators require information about the UAVs in order to to control them during their operations. UAVs need information to fly autonomously. A UAV flock needs to know the position of its center of mass to work effectively as a flock. Decision makers need to have information on the status of the UAVs. The list goes on. Communication of information is an essential element required for a flock of UAVs to perform any type of mission.

3.5.2 Information Model Assumptions.

In building an information model, the following assumptions were considered.

1. The individual UAVs in a group of UAVs have aerodynamically sound properties.
2. Unless otherwise noted, the group of UAVs is a homogeneous group or all of the vehicles are the same type with the same set of equipment. This reduces complexity

of the construction of the model. That said, the Information Model can easily accommodate a heterogenous group with slight modifications.

3. Information for transmission is finite, and is based on 'necessary information'.

   (a) There is a near infinite amount of information that can be gathered during the course of any mission, yet the amount of necessary information consists of information that is required to meet the objectives of the mission as ascertained by the predefined Measures of Performance (MOP) and Measures Of Effectiveness (MOE). For example, if a UAV flock is performing a surveillance mission where the goal is to observe any object that is human size or larger, it would be unnecessary to transmit the details of something as small as a mouse (though if the UAV flock was searching for Improvised Explosive Devices, something smaller may be important).

4. Information can be quantified according to a unit of information which can be transmitted in a variety of ways as decided by the engineer.

   (a) A unit of information is defined by: a generic word W (as described in Section 3.3.2), a collection of words k, a multiple of a collection of words ck where c is an integer, and a matrix of words k^j where $j \in \aleph$.

   (b) For an implementation in which bit rates are available, k will have a specific value for each s_i. For clarity of the final solution in this chapter, k is assumed to be approximately the same for each of the elements. This point is captured by referring to the order of k or o(k) when describing the number of words needed to encode s_i. Significant differences in the amount of words described by k are expressed through scalar multiples and exponential values of k.

5. Communication channels have a large enough bandwidth for the information flows required by the mission.

6. UAVs can always connect to the operator, either through another UAV or an intermediary, so that the goals or way points of the UAVs can be changed as needed during the mission.

(a) If communication is lost, the mission needs will dictate the operation of the UAV such that it will:

   i. Attempt to complete the mission

   ii. Terminate flight

   iii. Travel to home base or some other predefined position

(b) Information from sensors that have yet to be developed are not included in the current description of the Information Model.

7. Missions for UAVS can be broken into five different segments for which certain properties hold (refer Section 3.4.1 for segment descriptions).

   (a) Each segment is assumed to be the same length of time for the Sample Scenario. If differences in time length per segment need to be accounted for, the final expression of information requirements in terms of sampling rate for that segment would be multiplied by the amount of time the group of UAVs were in that segment.

   (b) The Current Model and Ideal Model have the same mission segment time lengths (and by extension the time length of the mission T is the same) so as to directly compare the models.

   (c) Segment t1 has equivalent information requirements as that of t5. This is similarly true between t2 and t4.

   (d) The Instantaneous Information is constant over the length of the segment.

8. UAV flocks of numbers greater than 1 communicate as a collective to the operator and vice versa. One method to accomplish this is by having the closest UAV to the operator pass on information to all of the other nearby UAVs and so on until the entire flock is notified (for more information see: Krill and O'Driscoll (2009)).

9. The emergence-based flocking model is developed to such a point that the UAV flock performs a mission nearly autonomously. While that does not mean that it needs to assign its own targets, it does imply that the UAV flock can find the centroid of the flock and provide meaningful data back to the operator, such as:

centroid current position, centroid heading, and centroid airspeed. A significant additional implication is that the UAVs under the Ideal Model also have the ability to aggregate video feeds into a single feed to send down to the operator. This required processing, for this thesis, does not increase Total Information.

10. The examination of the Current and Ideal Models is based on the assumption that the group of UAVs can remain in flight for the duration of the mission. As was seen in Seibert *et al.* (2010), landing, recovering, changing out the power supply, and relaunching a UAV all lead to a significant impact on the mission and would need to be accounted for if the mission duration is outside the likely range of the group of UAVs.

11. The Current Model, as is currently implemented for the OWL system, requires the ability for the operator to be able to take control of the individual UAV at any point during the mission via a remote control. The Ideal Model requires that the operator be able to control the UAV flock through waypoints at any given time.

3.5.3 UAV Information Model Header Elaboration. The terms that make up the Information Model represent a robust illustration of the types and amount of information needed for a group of UAVs to conduct any of the mission scenarios detailed in Section 3.1 either under the Current Model or the Ideal Model. The full list of categories identified to construct the Information Model are elaborated on below.

3.5.3.1 Index. For this heading category, S represents the full set of information for a single operator multiple UAV Information Model. It is composed of all the elements $(s_1, \ldots, s_n)$ such that $n \in \aleph$. For identification purposes, this indexing does not change for different subsets of S.

3.5.3.2 Component Name. Component Name captures the information element's primary concept. While it is possible to enumerate all information elements by uniquely indexing using the s_i element notation, some components are more logically left together, such as how a position is always described with two to three components.

Different representations of similar information types are presented in the General Model to illustrate differences in model construction.

3.5.3.3 Number of words needed. This refers to the number of words needed to encode the information for one instantiation for which the various information choices are explained in the next column. As developed in the assumptions for the model (Section 3.5.2), an integer corresponds to that number of words, k and any modifications, represents a variable sized amount of storage needed based on the level of detail desired for that component.

3.5.3.4 Explanation. Explanation details the different types of information for that component.

3.5.3.5 Example Data Source. This column provides a possible implementation to illustrate the types of devices that would provide the data of that element.

3.5.3.6 Repeated Information Storage. When Repeated Information Storage is populated with more than one entry per s_i, this represents a scalar multiple of the number of words needed for that s_i. This was introduced to capture the cases where that same type of information is needed in different ways, such as how a position type of information would be needed for both a UAV's current position and that of the Target's position.

3.5.3.7 Frequency of Update. This column illustrates the frequency of update or sampling rate per unit time (previously identified as Δt) for information transmission to any of the destinations that it may be required to go to. Because sampling rate is implementation dependent, four categories are presented to represent differing levels of transmission frequency. "None" refers to cases where the information was pre-loaded to the UAV and not transmitted during the mission. "Low" refers to an infrequent sampling rate. "Medium" refers to a semi-frequent sampling rate, and "High" refers to a frequent sampling rate. In the final evaluation, these categories correspond to multiples of the sampling rate (0, 100, 10 and 1 respectively).

3.5.3.8 Information Needed with Repeats. Information needed with repeats depicts the number of words needed per repeated information source while also uniquely linking to the frequency of update.

3.5.3.9 Path Segment. This column refers to the different mission segments for which the information element will be needed. Take Off (t1), Ingress (t2), Goal State (t3), Egress (t4), and Landing (t5) are all encoded by numerical entries 1, 2, 3, 4, and 5 respectively. For times when the information element is needed in all sections, the term All encoded by 6 will be used.

3.5.4 UAV flock Term Detailed Explanation. Some of the components described in the information table require expanded explanation beyond what is found in the Explanation column of the Information Model.

3.5.4.1 Identification Number or ID. Whenever the term Identification Number or ID is used in the Information Model, both the Operator and the UAV have a previously agreed upon unique and detailed database of information for which the ID number references.

3.5.4.2 Stereo Image for One Camera. Each of the three types of image generating payloads captured in the General Information Model (s_{33}, s_{34}, s_{35}) stem from a similar development. In order to understand all three, the Stereo Image will be expanded upon. The k^3 amount of information refers to a matrix which has an image pixel with two positions components and one color component. The 3 words corresponding to the geo-rectification refers to the position recorded for the image at one time. The 7 words needed for what is described as "various ID's" are drawn from the following representative list of important information:

1. Array Type
   (a) Area Arrays
   (b) Color Area Arrays

    (c) Linear Arrays
    (d) Color Linear Arrays
2. Array Size
3. Camera Frame Style
    (a) Large Format Frame
    (b) Medium Format Frame
    (c) Small Format Frame
    (d) Pushbroom Line Scanner
4. Number of Lens
5. Time
6. Spectral Band
    (a) Blue, Green, Red
    (b) Mid Infrared
    (c) Near Infrared
    (d) Thermal Infrared
7. Maximum Recording Rate

3.5.4.3 Bounded Goal State Area. This element is a collection of points that would generally be grouped under the position information element, but because of its importance to the Information Models under consideration, it was broken out as a unique element.

3.5.4.4 Mission Scenario: Goal State Area Logic and Execution Orders. This element refers to behavior that has yet to be developed that the UAV flock would employ inside the Goal Area as determined by the assigned mission. The numbers 1 through 16 correspond to each of the scenarios identified in Section 3.1.

3.5.4.5 Failure Conditions. Essentially, this element captures what each UAV must do if something goes wrong. These behaviors are pre-determined and are pre-loaded onboard the UAV before takeoff, though it also can be adjusted mid flight by an operator (such an action would likely be infrequent and is captured by the low sampling rate). The behavior logic will be activated based on UAV status indicator measurements.

3.5.5 UAV General Information Model Table. The General Information Model was developed to address the instantaneous information needs of one UAV over the course of a variety of scenarios. Many different implementations can be derived from this table, such as in the manner that the Current and Ideal Models will be developed, and it is unlikely that one UAV would have all of the different information elements. The information elements were selected based on the following sources: the autopilot development thesis of Reed Christiansen (2004), experience gained through work with the OWL platform (Seibert *et al.*, 2010), remote sensing papers ((Schiewe, 2005) and (Petrie and Walker, 2007)), and the information requirements gleaned from the development of the emergence-based flocking model (Section 2.5). The set of four tables that encompass the General Information Model are shown sequentially in Table 3.1*a* to Table 3.1*d*.

Table 3.1*a*: General Information Model

General Information Model								
Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_1	Position	3	single point in space consisting of 3 elements; x, y, and z. In the case of mission path, a string of k length of points	position measurement	UAV Current	High	3	6
					UAV Desired	Low	3	
					Target	Low	3	
					Mission Path or string of points	Low	3k	
s_2	Heading	1	direction that the aircraft's nose is pointing	heading indicator	UAV Current	High	2	6
					UAV Desired	Low	2	
s_3	Airspeed	1	air speed	pitot tube	UAV Current	High	2	6
					UAV Desired	Low	2	
s_4	Groundspeed	1	ground distance covered per unit time	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_5	Yaw	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_6	Pitch	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_7	Roll	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_8	Height Above Ground	1	distance between the aircraft center of mass and the ground	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_9	Fuel Level	1	percentage of fuel remaining	float and potentiometer	UAV Current	High	1	6
s_{10}	Rudder	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{11}	Elevator	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{12}	Ailerons	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{13}	Spoilers	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{14}	Flaps	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	

Table 3.1*b*: General Information Model (continued, p.2)

Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_{15}	Slats	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{16}	Air Breaks	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{17}	RPM	1	number of revolutions of a propeller based engine	system sensor	UAV Current	High	1	6
s_{18}	Electrical Power Level	1	electrical systems power supply	voltmeter	UAV Current	High	1	6
s_{19}	Landing Gear Position	1	angular offset from reference axis	system sensor	UAV Current	High	1	6
s_{20}	Internal Temperatures	1	measuring internal temperature	thermometer	UAV Current	High	1	6
s_{21}	Hydraulic Pressure	1	as appropriate for engine type	pressure gauge	UAV Current	High	1	6
s_{22}	System Quality	o(k)	systems functional status; can include k different indicators	system sensor	UAV Current	High	k	6
s_{23}	GPS Satellite Count	1	a significant number of satellites need to be acquired for GPS use	GPS strong signal count	UAV Current	High	2	6
s_{24}	Time	6	fully detailed to required level (Year, Month, Day, Hour, Min, Second)	internal clock	UAV	Low	6	6
					Target	Low	6	
s_{25}	External to UAV Temperature	1	measuring temperature	thermometer	UAV	Low	1	3
s_{26}	Terrain Map	$o(k^3)$	pre-loaded terrain map, with 3 words to describe each pixel	mission command	UAV	None	k^3	2,3,4
		1	ID # for detail level			None	1	
s_{27}	Condensation Level	1	measuring condensation	wet bulb	UAV	Low	1	3
s_{28}	Atmospheric Pressure	1	measuring pressure	mercury barometer	UAV	Low	1	3

Table 3.1*c*: General Information Model (continued, p.3)

Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_{29}	Light Intensity	1	measuring light	photometer	UAV	Low	1	3
s_{30}	Number of Functional UAVs Within Formation	1	continuously monitored	sensors or transponder	UAV	High	1	6
s_{31}	Munitions Type	o(k)	ID # corresponding to preloaded database	aircraft instruments	UAV	Low	k	6
s_{32}	Munitions Quantity	o(k)	quantity of each ID #	mission command	UAV	Low	k	6
s_{33}	Stereo Image For One Camera	$o(k^3)$	represents a k x k matrix of pixels for a 2D image with color assignment	image generated from a small format frame, CCD array camera	UAV	High	k^3	3
		3	geo-rectification of the image	position of the camera		High	3	3
		7	various ID's describing the stereo image system	mission command		Low	7	6
s_{34}	3D Stereo Model For One Camera	$o(k^4)$	represents a k x k x k matrix of pixels for a 3D image with color assignment	image generated from a medium format, CCD array camera	UAV	High	k^4	3
		3	geo-rectification of the image	position of the camera		High	3	3
		7	various ID's describing the stereo image system	mission command		Low	7	6
s_{35}	Multispectral Model for One Camera	$o(k^4)$	represents a k x k x k matrix of pixels for a 3D image with color assignment	image generated from a large format, CCD array camera	UAV	High	k^4	3
		3	geo-rectification of the image	position of the camera		High	3	3
		7	various ID's describing the stereo image system	mission command		Low	7	6
s_{36}	Radar Type	1	ID # corresponding to preloaded database	mission command	UAV	Low	1	6

Table 3.1*d*: General Information Model (continued, p.4)

Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_{37}	Radar Type Quantity	1	Quantity of each ID #	mission command	UAV	Low	1	6
s_{38}	Electronic Combat (EC) Devices	o(k)	ID # corresponding to preloaded database	mission command	UAV	Low	k	6
s_{39}	EC Devices Quantity	o(k)	Quantity of each ID #	mission command	UAV	Low	k	6
s_{40}	Mission Scenario: Goal State Area Logic And Execution Orders	o(k)	Chosen from (1-16) predefined missions with behaviors, can be strung together for a multiple scenario mission plan	operator can adjust	UAV	Low	k	3
				mission command		None	k	3
s_{41}	Bounded Goal State Area	o(3k)	A series of points that defines the polygonal area the flock must stay within during Goal State	operator can adjust	UAV	Low	3k	2,3,4
				mission command		None	3k	2,3,4
s_{42}	UAV Flock Rules and Weights	o(k)	Parameters adjusted in mission	operator can adjust	UAV	Low	k	6
			Pre-loaded parameters	mission		None	k	6
s_{43}	Failure Conditions	o(k)	preloaded parameters that address what constitutes a failure for the vehicle (i.e. low battery level)	operator can adjust	UAV	Low	k	6
				mission command		None	k	6
s_{44}	Failure Behaviors	o(k)	preloaded parameters that address actions to take once a failure is determined	operator can adjust	UAV	Low	k	6
				mission command		None	k	6
s_{45}	Measures of Effectiveness (MOEs)	o(k)	methodology to determine effectiveness of mission	operator can adjust	UAV	Low	k	3
				mission command		None	k	3
s_{46}	Measures of Performance (MOPs)	o(k)	methodology to evaluate performance during a mission	operator can adjust	UAV	Low	k	3
				mission command		None	k	3
s_{47}	Air Tasking Order	o(k)	Mission Planners assign the UAV Flock as part of the overall mission	operator can adjust	UAV	Low	k	6
				mission command		None	k	6

3.6 Current Model Instantaneous Information

The Current Model was initially described in Section 1.2.1. The Instantaneous Information for the Current Model, including all Mission Segments, is presented starting in Table 3.2a and continues on to a second page. Construction of the Information Model was based on the information requirements of one OWL vehicle (Seibert *et al.*, 2010) needed to be used and or communicated between the UAV and the operator over the course of the sample scenario. It represents a subset of the General Information Model and requires all of the same assumptions.

Table 3.2*a*: Current Model Instantaneous Information

Information needed to be passed between the Operator and one UAV under the Current Model at any point along the mission path								
Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_1	Position	3	single point in space consisting of 3 elements; x, y, and z. In the case of mission path, a string of k length of points	position measurement	UAV Current	High	3	6
					UAV Desired	Low	3	
					Target	Low	3	
					Mission Path or string of points	Low	3k	
s_2	Heading	1	direction that the aircraft's nose is pointing	heading indicator	UAV Current	High	2	6
					UAV Desired	Low	2	
s_3	Airspeed	1	air speed	pitot tube	UAV Current	High	2	6
					UAV Desired	Low	2	
s_4	Groundspeed	1	ground distance covered per unit time	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_5	Yaw	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_6	Pitch	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_7	Roll	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_8	Height Above Ground	1	distance between the aircraft center of mass and the ground	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{10}	Rudder	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{12}	Ailerons	1	angular offset from reference axis	system sensor	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{17}	RPM	1	number of revolutions of a blade based engine	system sensor	UAV Current	High	1	6

Table 3.2*b*: Current Model Instantaneous Information (p.2)

Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_{18}	Electrical Power Level	1	electrical systems power supply	voltmeter	UAV Current	High	1	6
s_{22}	System Quality	o(k)	systems functional status; can include k different indicators	system sensor	UAV Current	High	k	6
s_{23}	GPS Satellite Count	1	a significant number of satellites need to be acquired for GPS use	GPS strong signal count	UAV Current	High	1	6
s_{24}	Time	6	fully detailed to required level (Year, Month, Day, Hour, Min, Second)	internal clock	UAV	Low	6	6
					Target	Low	6	
s_{26}	Terrain Map	o(k^3)	pre-loaded terrain map, with 3 words to describe each pixel	mission command	UAV	None	k^3	6
		1	ID # for detail level			None	1	
s_{33}	Stereo Image For One Camera	o(k^3)	represents a k x k matrix of pixels for a 2D image with color assignment	image generated from a small format frame, CCD array camera	UAV	High	k^3	3
		3	geo-rectification of the image	position of the camera		High	3	3
		7	various ID's describing the stereo image system	mission command		Low	7	2,3,4
s_{43}	Failure Conditions	o(k)	preloaded parameters that address what constitutes a failure for the vehicle (i.e. low battery level)	operator can adjust	UAV	Low	k	6
				mission command		None	k	6
s_{44}	Failure Behaviors	o(k)	preloaded parameters that address actions to take once a failure is determined	operator can adjust	UAV	Low	k	6
				mission command		None	k	6

3.7 Ideal Model Instantaneous Information

The Ideal Model was initially described in Section 1.2.2. The Instantaneous Information for the Ideal Model, including all Mission Segments, is presented beginning with Table 3.3*a* and continues on to a second page. Construction of the model was based primarily on an application of the emergence based flocking model to one OWL vehicle (Seibert *et al.*, 2010) and the information required over the course of the sample scenario. It represents a subset of the General Information Model and requires all of the same assumptions. A significant difference between this model and the Current Model, is that in this model, every element of information that corresponds to one vehicle actually represents an average of all vehicles in the flock; most simply, this can be understood in that the centroid of the UAV flock has most all of the characteristics of a single UAV. The averaging is performed within the UAV flock and communicated to the operator. As a result, the operator is effectively managing a single UAV controlled by waypoint navigation. Note: the operator would likely see on his or her interface, a bounding shape of the flock which visually summarizes all of the information sent to the operator at that point in time.

Table 3.3a: Ideal Model Instantaneous Information

Information needed to be passed between the operator and the UAV Flock under the Ideal Model at any point along the mission path								
Index	**Component Name**	**# of Words Needed**	**Explanation**	**Example Data Source**	**Repeated Information Storage, Described By Name of Source**	**Frequency of Update: None Low Med High**	**Info. Needed With Repeats**	**Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)**
s_1	Position	3	single point in space consisting of 3 elements; x, y, and z. In the case of mission path, a string of k length of points	position measurement	UAV Current	High	3	6
					UAV Desired	Low	3	
					Target	Low	3	
					Mission Path or string of points	Low	3k	
s_2	Heading	1	direction that the aircraft's nose is pointing	heading indicator	UAV Current	High	2	6
					UAV Desired	Low	2	
s_3	Airspeed	1	air speed	pitot tube	UAV Current	High	2	6
					UAV Desired	Low	2	
s_4	Groundspeed	1	ground distance covered per unit time	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_5	Yaw	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_6	Pitch	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_7	Roll	1	angular offset from reference axis	magnetometer	UAV Current	High	2	6
					UAV Desired	Low	2	
s_8	Height Above Ground	1	distance between the aircraft center of mass and the ground	GPS	UAV Current	High	2	6
					UAV Desired	Low	2	
s_{18}	Electrical Power Level	1	electrical systems power supply	voltmeter	UAV Current	High	1	6
s_{22}	System Quality	o(k)	systems functional status; can include k different indicators	system sensor	UAV Current	High	k	6
s_{23}	GPS Satellite Count	1	a significant number of satellites need to be acquired for GPS use	GPS strong signal count	UAV Current	High	1	6
s_{24}	Time	6	fully detailed to required level (Year, Month, Day, Hour, Min, Second)	internal clock	UAV	Low	6	6
					Target	Low	6	
s_{26}	Terrain Map	$o(k^3)$	pre-loaded terrain map, with 3 words to describe each pixel	mission command	UAV	None	k^3	6
		1	ID # for detail level			None	1	

Table 3.3*b*: Ideal Model Instantaneous Information (p.2)

Index	Component Name	# of Words Needed	Explanation	Example Data Source	Repeated Information Storage, Described By Name of Source	Frequency of Update: None Low Med High	Info. Needed With Repeats	Path Segment: Take Off (1) Ingress (2) Goal State (3) Egress (4) Landing (5) All (6)
s_{30}	Number of Functional UAVs Within Formation	1	continuously monitored	sensors or transponder	UAV	High	1	6
s_{33}	Stereo Image For One Camera	$o(k^3)$	represents a k x k matrix of pixels for a 2D image with color assignment	image generated from a small format frame, CCD array camera	UAV	High	k^3	3
		3	geo-rectification of the image	position of the camera		High	3	3
		7	various ID's describing the stereo image system	mission command		Low	7	2,3,4
s_{40}	Mission Scenario: Goal State Area Logic And Execution Orders	o(k)	Chosen from (1-16) predefined missions with behaviors, can be strung together for a multiple scenario mission plan	operator can adjust	UAV	Low	k	3
				mission command		None	k	3
s_{41}	Bounded Goal State Area	o(3k)	A series of points that defines the polygonal area the flock must stay within during Goal State	operator can adjust	UAV	Low	3k	2,3,4
				mission command		None	3k	2,3,4
s_{42}	UAV Flock Rules and Weights	o(k)	Parameters adjusted in mission	operator can adjust	UAV	Low	k	6
			Pre-loaded parameters	mission command		None	k	6
s_{43}	Failure Conditions	o(k)	preloaded parameters that address what constitutes a failure for the vehicle (i.e. low battery level)	operator can adjust	UAV	Low	k	6
				mission command		None	k	6
s_{44}	Failure Behaviors	o(k)	preloaded parameters that address actions to take once a failure is determined	operator can adjust	UAV	Low	k	6
				mission command		None	k	6
s_{45}	Measures of Effectiveness (MOEs)	o(k)	methodology to determine effectiveness of mission	operator can adjust	UAV	Low	k	3
				mission command		None	k	3
s_{46}	Measures of Performance (MOPs)	o(k)	methodology to evaluate performance during a mission	operator can adjust	UAV	Low	k	3
				mission command		None	k	3

3.8 Total Information Calculation

With the respective models now detailed, it remains to find the Total Information of each model over the course of the sample scenario. To do this, first the various Instantaneous Information requirements for given segments were identified with any repeats, the Information Density function was developed, and then the Total Information evaluation per segment and in total was performed.

3.8.1 Information Summation by Mission Segment. The mission segment tables capture the amount of words needed for each segment of the mission with the frequency of update variables left unconverted. As was noted in the assumptions, segments t1 and t2 are equivalent in structure to t5 and t4 respectively. Table 3.4 describes the information requirements for segment t1, Table 3.5 details the information requirements for segment t2, and lastly, Table 3.6 describes the information requirements for segment t3.

Table 3.4: Comparing Models: Mission Segment t1 (and t5)

Mission Segment t1 (Identical to t5)		
Component Name	**Current Model** Number of Words Required	**Ideal Model** Number of Words Required
Position	3High + (3k +6)Low	3High + (3k +6)Low
Heading	2High + 2Low	2High + 2Low
Airspeed	2High + 2Low	2High + 2Low
Groundspeed	2High + 2Low	2High + 2Low
Yaw	2High + 2Low	2High + 2Low
Pitch	2High + 2Low	2High + 2Low
Roll	2High + 2Low	2High + 2Low
Height Above Ground	2High + 2Low	2High + 2Low
Rudder	2High + 2Low	-
Ailerons	2High + 2Low	-
RPM	2High + 2Low	-
Electrical Power Level	2High + 2Low	2High + 2Low
System Quality	kHigh	kHigh
GPS Satellite Count	High	High
Time	12Low	12Low
Terrain Map	$(k^3 + 1)$None	$(k^3 + 1)$None
Number of Functional UAVs in Formation	-	High
UAV Flock Rules and Weights	-	kLow + kNone
Failure Conditions	kLow + kNone	kLow + kNone
Failure Behaviors	kLow + kNone	kLow + kNone
Segment t1 Information Density	(k + 26)High + (5k + 40)Low + $(k^3 + 2k + 1)$None	(k + 21)High + (6k + 34)Low + $(k^3 + 3k + 1)$None

Table 3.5: Comparing Models: Mission Segment t2 (and t4)

Mission Segment t2 (Identical to t4)		
Component Name	**Current Model** Number of Words Required	**Ideal Model** Number of Words Required
Position	3High + (3k +6)Low	3High + (3k +6)Low
Heading	2High + 2Low	2High + 2Low
Airspeed	2High + 2Low	2High + 2Low
Groundspeed	2High + 2Low	2High + 2Low
Yaw	2High + 2Low	2High + 2Low
Pitch	2High + 2Low	2High + 2Low
Roll	2High + 2Low	2High + 2Low
Height Above Ground	2High + 2Low	2High + 2Low
Rudder	2High + 2Low	-
Ailerons	2High + 2Low	-
RPM	2High + 2Low	-
Electrical Power Level	2High + 2Low	2High + 2Low
System Quality	kHigh	kHigh
GPS Satellite Count	High	High
Time	12Low	12Low
Terrain Map	$(k^3 + 1)$None	$(k^3 + 1)$None
Number of Functional UAVs in Formation	-	High
Stereo Image for One Camera	7 Low	7 Low
Bounded Goal State Area	-	kLow + kNone
UAV Flock Rules and Weights	-	kLow + kNone
Failure Conditions	kLow + kNone	kLow + kNone
Failure Behaviors	kLow + kNone	kLow + kNone
Measures of Effectiveness (MOEs)	-	kLow + kNone
Measures of Performance (MOPs)	-	kLow + kNone
Segment t2 Information Density	(k + 26)High + (5k + 47)Low +$(k^3 + 2k + 1)$None	(k + 21)High + (9k + 41)Low +$(k^3 + 6k + 1)$None

Table 3.6: Comparing Models: Mission Segment t3

Mission Segment t3		
Component Name	**Current Model** Number of Words Required	**Ideal Model** Number of Words Required
Position	3High + (3k +6)Low	3High + (3k +6)Low
Heading	2High + 2Low	2High + 2Low
Airspeed	2High + 2Low	2High + 2Low
Groundspeed	2High + 2Low	2High + 2Low
Yaw	2High + 2Low	2High + 2Low
Pitch	2High + 2Low	2High + 2Low
Roll	2High + 2Low	2High + 2Low
Height Above Ground	2High + 2Low	2High + 2Low
Rudder	2High + 2Low	-
Ailerons	2High + 2Low	-
RPM	2High + 2Low	-
Electrical Power Level	2High + 2Low	2High + 2Low
System Quality	kHigh	kHigh
GPS Satellite Count	High	High
Time	12Low	12Low
Terrain Map	$(k^3 + 1)$None	$(k^3 + 1)$None
Number of Functional UAVs in Formation	-	High
Stereo Image for One Camera	$(k^3 + 3)$High + 7 Low	$(k^3 + 3)$High + 7 Low
Mission Scenario: Goal State Area Logic And Execution Orders	-	kLow + kNone
Bounded Goal State Area	-	kLow + kNone
UAV Flock Rules and Weights	-	kLow + kNone
Failure Conditions	kLow + kNone	kLow + kNone
Failure Behaviors	kLow + kNone	kLow + kNone
Measures of Effectiveness (MOEs)	-	kLow + kNone
Measures of Performance (MOPs)	-	kLow + kNone
Segment t3 Information Density	$(k^3 + k + 29)$High + (5k + 47)Low +$(k^3 + 2k + 1)$None	$(k^3 + k + 24)$High + (10k + 41)Low +$(k^3 + 7k + 1)$None

3.8.2 Total Information. The Total Information Table 3.7 presents the Information Density functions from t1 through t5. Following this column for each of the models, the Total Information is calculated per segment with a final summation describing the Total Information requirements for the full 90 minute Sample Scenario.

Table 3.7: Total Information Compared

Total Information (One UAV or N = 1)				
Segment Subtotal	**Current Model** Information Density; High = 1/1, Med = 1/10, Low = 1/100, None = 0	**Current Model** Total Information (multiplied by segment Time Length and applied numerical frequency of update)	**Ideal Model** Information Density; High = 1/1, Med = 1/10, Low = 1/100, None = 0	**Ideal Model** Total Information (multiplied by segment Time Length and applied numerical frequency of update)
Segment t1: Time Length = 12 Min	(k + 26)High + (5k + 40)Low + (k^3 + 2k +1)None	12.6k + 316.8	(k + 21)High + (6k + 34)Low + (k^3 + 3k +1)None	12.72k + 256.08
Segment t2: Time Length = 10 Min	(k + 26)High + (5k + 47)Low +(k^3 + 2k + 1)None	10.5k + 264.7	(k + 21)High + (9k + 41)Low +(k^3 + 6k + 1)None	10.9k + 214.1
Segment t3: Time Length = 46 Min	(k^3 + k + 29)High + (5k + 47)Low +(k^3 + 2k + 1)None	$46k^3$ + 48.3k + 1355.62	(k^3 + k + 24)High + (10k + 41)Low +(k^3 + 7k + 1)None	$46k^3$ + 50.6k + 1105.84
Segment t4 Identical to Segment t2	(k + 26)High + (5k + 47)Low +(k^3 + 2k + 1)None	10.5k + 264.7	(k + 21)High + (9k + 41)Low +(k^3 + 6k + 1)None	10.9k + 214.1
Segment t5 Identical to Segment t1	(k + 26)High + (5k + 40)Low + (k^3 + 2k +1)None	12.6k + 316.8	(k + 21)High + (6k + 34)Low + (k^3 + 3k +1)None	12.72k + 256.08
Full 90 Minute Mission, Total Information		$46k^3$ + 94.5k + 2518.62		$46k^3$ + 97.84k + 2046.2

3.9 Comparative Analysis

The results of the comparison of the two model's Total Information as seen in Table 3.7. If the group of UAVs in either the Current Model of the Ideal Model consists of just a single vehicle, the Total Information required for the emergence based flocking rules to be implemented (Ideal Model) is less than that of the operator controlling one vehicle in the Current Model. This makes sense because the Ideal Model is more autonomous than the Current Model, and therefore over the length of the Sample Scenario, less information needs to be passed from the operator to the UAV. This situation is visually captured in Figure 3.2, where k was set equal to 15 in order to have a single value of information at each segment for both the Current and Ideal Model. The volume of the ellipses is scaled to illustrate the differences in information by setting the volume approximately equal to the number of words needed for that segment. The notable exception is that due to the Goal State's massive difference between the other segments (68 times as large), it was simply significantly larger in comparison to the others.

When there are 10 vehicles in the group of UAVs, the situation drastically changes. Under the Current Model, as there is a linear increase in information requirements, each additional vehicle to the group of UAVs requires an additional and identical set of the measured Total Information for one UAV. For the Ideal Model, increases in the number of UAVs leads to no appreciable increase in the amount of information sent between the operator and the UAV flock. This situation is captured in Figure 3.3 for which k again equals 15, but now the Current Model has had the amount of words in each segment multiplied by 10 while the Ideal Model's number of words has remained the same.

The lack of increase in the amount of information under the Ideal Model was discussed in the assumptions of the General Information Model 3.5.2, but to reiterate, the key idea is that the operator is controlling the flock essentially as if it was one UAV. For example, the UAV flock is responsible for aggregating and transmitting to the operator a single stereo image composed of all the flock member's contributions and distributing the operator's commands amongst the flock. Even without this assumption, it can readily be seen from the Current and Ideal Model's Instantaneous Information

Tables that the Ideal Model reduces the amount of Total Information the operator must process.

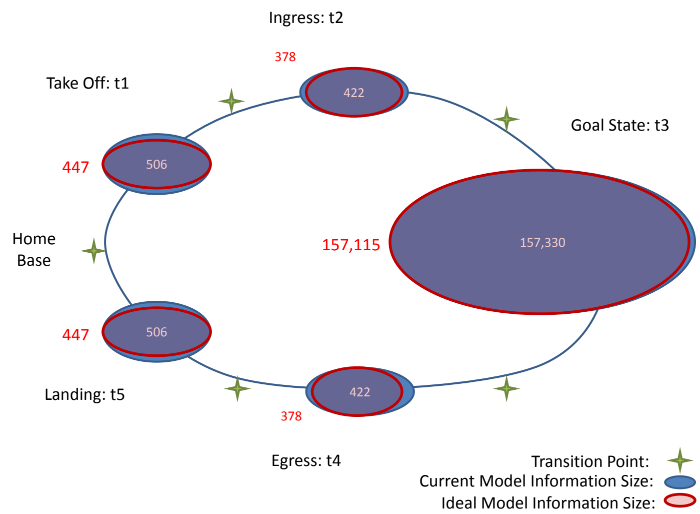

Figure 3.2: Total Information Visual Comparison: One UAV (for k=15)

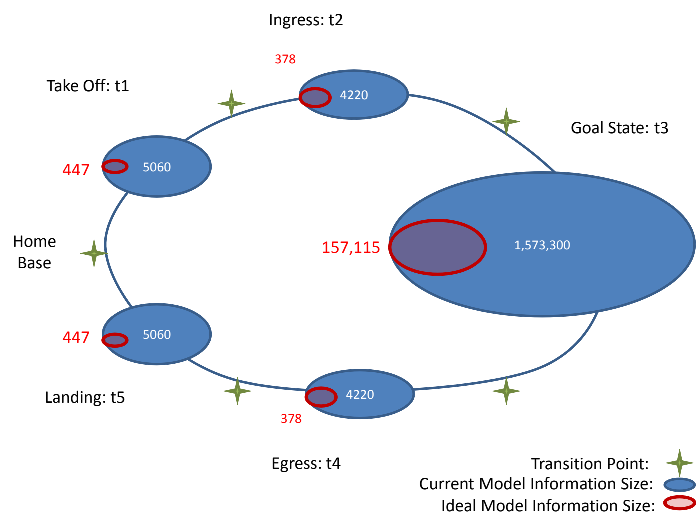

Figure 3.3: Total Information Visual Comparison: Ten UAVs (for k=15)

The more general case where the number of vehicles in the group of UAVs (N) varies along with the number of words (k) is presented in Table 3.8 for the case of the Current Model, the Ideal Model, and the difference between the two models. As can be seen from the difference table, the number of words required over the length of the 90 minute Sample Scenario is much less under the Ideal Model than the Current Model, especially as k and N increase. This is consistent with what was shown in the snapshots of Total Information requirements per segment in Figures 3.2 and 3.3. As a result of this analysis, it is clear that the operator will have a significantly easier time managing multiple UAVs under the Ideal Model than under the Current Model.

Table 3.8: Varying N and k for the Current Model, Ideal Model, and the Difference Between the Two

Total Information for the Current Model, with k and N varying . The lighter the color, the lower the count of words needed for that combination of N and k.

		N												
		1	2	3	4	5	6	7	8	9	10	11	12	13
k	1	2.66E+03	5.32E+03	7.98E+03	1.06E+04	1.33E+04	1.60E+04	1.86E+04	2.13E+04	2.39E+04	2.66E+04	2.93E+04	3.19E+04	3.46E+04
	2	3.08E+03	6.15E+03	9.23E+03	1.23E+04	1.54E+04	1.85E+04	2.15E+04	2.46E+04	2.77E+04	3.08E+04	3.38E+04	3.69E+04	4.00E+04
	3	4.04E+03	8.09E+03	1.21E+04	1.62E+04	2.02E+04	2.43E+04	2.83E+04	3.24E+04	3.64E+04	4.04E+04	4.45E+04	4.85E+04	5.26E+04
	4	5.84E+03	1.17E+04	1.75E+04	2.34E+04	2.92E+04	3.50E+04	4.09E+04	4.67E+04	5.26E+04	5.84E+04	6.42E+04	7.01E+04	7.59E+04
	5	8.74E+03	1.75E+04	2.62E+04	3.50E+04	4.37E+04	5.24E+04	6.12E+04	6.99E+04	7.87E+04	8.74E+04	9.62E+04	1.05E+05	1.14E+05
	6	1.30E+04	2.60E+04	3.91E+04	5.21E+04	6.51E+04	7.81E+04	9.12E+04	1.04E+05	1.17E+05	1.30E+05	1.43E+05	1.56E+05	1.69E+05
	7	1.90E+04	3.79E+04	5.69E+04	7.58E+04	9.48E+04	1.14E+05	1.33E+05	1.52E+05	1.71E+05	1.90E+05	2.09E+05	2.27E+05	2.46E+05
	8	2.68E+04	5.37E+04	8.05E+04	1.07E+05	1.34E+05	1.61E+05	1.88E+05	2.15E+05	2.41E+05	2.68E+05	2.95E+05	3.22E+05	3.49E+05
	9	3.69E+04	7.38E+04	1.11E+05	1.48E+05	1.85E+05	2.21E+05	2.58E+05	2.95E+05	3.32E+05	3.69E+05	4.06E+05	4.43E+05	4.80E+05
	10	4.95E+04	9.89E+04	1.48E+05	1.98E+05	2.47E+05	2.97E+05	3.46E+05	3.96E+05	4.45E+05	4.95E+05	5.44E+05	5.94E+05	6.43E+05
	11	6.48E+04	1.30E+05	1.94E+05	2.59E+05	3.24E+05	3.89E+05	4.53E+05	5.18E+05	5.83E+05	6.48E+05	7.13E+05	7.77E+05	8.42E+05
	12	8.31E+04	1.66E+05	2.49E+05	3.33E+05	4.16E+05	4.99E+05	5.82E+05	6.65E+05	7.48E+05	8.31E+05	9.15E+05	9.98E+05	1.08E+06
	13	1.05E+05	2.10E+05	3.14E+05	4.19E+05	5.24E+05	6.29E+05	7.34E+05	8.38E+05	9.43E+05	1.05E+06	1.15E+06	1.26E+06	1.36E+06
	14	1.30E+05	2.60E+05	3.90E+05	5.20E+05	6.50E+05	7.80E+05	9.10E+05	1.04E+06	1.17E+06	1.30E+06	1.43E+06	1.56E+06	1.69E+06
	15	1.59E+05	3.18E+05	4.78E+05	6.37E+05	7.96E+05	9.55E+05	1.11E+06	1.27E+06	1.43E+06	1.59E+06	1.75E+06	1.91E+06	2.07E+06

Total Information for the Ideal Model, with k and N varying . The lighter the color, the lower the count of words needed for that combination of N and k.

		N												
		1	2	3	4	5	6	7	8	9	10	11	12	13
k	1	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03	2.19E+03
	2	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.61E+03
	3	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03	3.58E+03
	4	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03	5.38E+03
	5	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03
	6	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04
	7	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04	1.85E+04
	8	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04	2.64E+04
	9	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04	3.65E+04
	10	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04	4.90E+04
	11	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04	6.43E+04
	12	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04	8.27E+04
	13	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05	1.04E+05
	14	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05	1.30E+05
	15	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05	1.59E+05

Comparison Table: Value in cell = Current Model - Ideal Model. The darker the color, the smaller the difference.

		N												
		1	2	3	4	5	6	7	8	9	10	11	12	13
k	1	469	3128	5787	8446	11106	13765	16424	19083	21742	24401	27060	29719	32379
	2	466	3541	6617	9693	12768	15844	18919	21995	25071	28146	31222	34298	37373
	3	462	4507	8551	12595	16639	20683	24727	28771	32815	36859	40904	44948	48992
	4	459	6300	12140	17981	23822	29662	35503	41343	47184	53025	58865	64706	70547
	5	456	9197	17938	26679	35420	44161	52902	61644	70385	79126	87867	96608	105349
	6	452	13474	26496	39517	52539	65560	78582	91604	104625	117647	130669	143690	156712
	7	449	19407	38365	57323	76282	95240	114198	133156	152114	171072	190030	208988	227946
	8	446	27272	54099	80926	107752	134579	161405	188232	215059	241885	268712	295539	322365
	9	442	37345	74249	111152	148055	184958	221861	258764	295667	332570	369474	406377	443280
	10	439	49903	99366	148830	198294	247757	297221	346684	396148	445612	495075	544539	594002
	11	436	65220	130004	194788	259572	324356	389140	453925	518709	583493	648277	713061	777845
	12	432	83573	166714	249854	332995	416135	499276	582417	665557	748698	831839	914979	998120
	13	429	105238	210047	314856	419665	524475	629284	734093	838902	943711	1048520	1153329	1258138
	14	426	130491	260557	390623	520688	650754	780819	910885	1040951	1171016	1301082	1431147	1561213
	15	422	159608	318795	477981	637167	796353	955539	1114725	1273911	1433097	1592284	1751470	1910656

IV. Thesis Conclusion and Future Work

4.1 Conclusion

As the USAF becomes increasingly reliant on UAVs and demands cost-savings wherever possible, a solution to min(O/V) becomes necessary. This thesis presented such a solution through proposing an emergence-based flocking model and evaluating that model based on the information requirements of a single operator managing a UAV flock over the course of a sample scenario as compared to a single operator controlling a group of UAVs in what is called the Current Model.

The emergence-based flocking behavior model placed the majority of information processing on the UAVs and within the UAV flock as a whole rather than the operator. This significantly aids in the reduction of information transmitted between the operator and the UAVs. As a result, the operator is freed to do other activities, such as managing multiple UAV flocks or analyzing surveillance video more effectively.

Developing an Information Model to evaluate the Current and Ideal Models generates a sound bridge between theoretical architecture and engineered solutions. Considering information in the abstract sense over the course of a mission proves to be a common language between these two disciplines. The advantage of constructing an architecture on an abstract foundation is that it is particularly resilient to differences in implementations. It provides a general solution for which engineers can develop impressive systems while still being able to communicate with other engineers in different groups all the while increasing the ease with which systems can be integrated.

In summary, the Ideal Model presented in this thesis serves as an excellent platform with which to move forward in the development of single operator management of multiple UAVs as significant troubles are present with the Current Model with which the Ideal Model rectifies. Additionally, the requirement of the USAF by the end of 2047 that "fewer operators will be 'flying' the sorties but directing swarms of aircraft" (Headquarters, United States Air Force, 2009b), indicates that the Ideal Model is necessary. With the accompanying road map presented in the Sections of future research and recommendations, the USAF has a robust solution moving towards the 2047 goal.

4.2 Future Research

The nature of this thesis presents many different areas that can be pursued so as to develop a solid implementation of a solution to min(O/V). Some notable sections are listed here.

4.2.1 Emergence Based Flocking Rule Weighting. Many researchers have developed different flocking models, and the greatest common challenge with this type of model is in developing a weighting schema for the rules that is robust to changes in the mission. One potential track to follow would be that of a genetic algorithm which would iteratively attempt solutions for appropriate weightings to Equation 2.1, improving upon itself over time, to the point where a robust methodology is developed. This stands as an important area of future research for effective emergence based flocking implementations.

4.2.2 Full single operator multiple UAV Information Model Development. While the full development was outside the scope of this thesis, such an effort would yield great dividends. If all systems were constructed on a flexible architecture that is the Information Model, integration of disparate systems would be greatly improved. Furthermore, vehicles would have a much simpler time establishing communications links with each other. It is not necessary to fully redevelop vehicles for integration into the architecture. A simple transformation and mapping of like information to like information would likely achieve this goal.

4.2.3 Information Space. An Information Space represents a precise way to organize and discuss real world data. Currently, there are a few different methods of modeling information. The method under consideration in this thesis was that of a mathematical model composed of an instantaneous and total information set (or list). The information set described the details of the data using such descriptors as type, amount, structure, and salient properties within a particular limited context. Limiting the context is crucial as all information in the world would be impossible to fully model, but various narrowed categories can be modeled to a defined level of detail.

Beyond simply describing the data through a vast list, research should examine the creation of an Information Space, which could possibly adhere to the rules of a vector space. In order to prove this, the necessary operations on the space of vector addition, scalar multiplication, and the presence of an identity vector need to be demonstrated.

After proof that information can be described by a vector space, applied research should demonstrate the case for one or more UAVs designed to perform either alone or within a UAV flock. The volume of information over the entire path (trajectory through a space) of a mission will stem from, among other necessary elements, a definition of a measure (or metric) appropriate on the information space. Initial foundations for this work was undertaken, but the research was not completed, and removed from this thesis.

4.2.4 Fractal Architecture. UAV flocks must process a significant amount of information over the course of a standard mission, as was documented by the Information Model. Even with emergence-based rules applied, UAVs must still perform complex tasks that demand great complexity of each UAV involved in the mission. One possible solution around the hurdle of mandatory complexity comes in the form of distributed processing of information.

UAVs can range in size from the large RQ-4 Global Hawk down to very small or nano size air vehicles. While a large UAV like the Global Hawk can carry a large set of payloads, the vehicles are very complex and expensive to operate. On the other hand, nano air vehicles have the potential to accomplish significant feats if they can work together. Consider this example based on research conducted by Fritz B. Prinz at the University of Stanford; it has been demonstrated that tiny, low powered air vehicles are possible (Prinz, 1999). If each of these nano vehicles came equipped with a one (or a few) pixel CCD array, with a transmitter and some method of geo-rectification, an image of varying quality and size could determined by the number of nano vehicles employed. One way to accomplish such a task is through distributing processing of information.

Real-time distributed architectures could to manage complex tasks across a flock of UAVs, particularly when the vehicles are individually too small to provide the full requisite computing capacity. Such architectures include compressed message Service Oriented

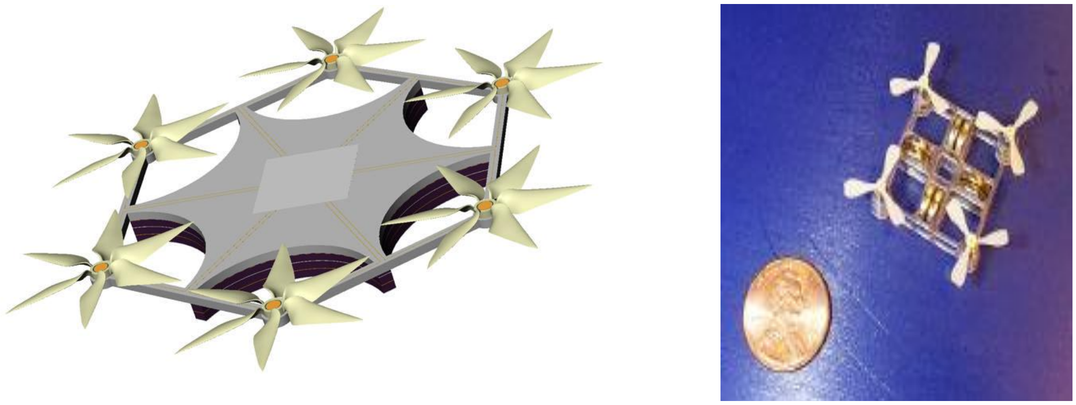

Figure 4.1: Conceptual and Implemented nano copters (Prinz, 1999)

Architecture (SOA) processes, agent computing, and grid computing (Erl, 2005). While considering work in this way is not new, the method of construction is more novel.

Fractals exhibit emergent characteristics in a similar manner to that of bird flocks. Iteratively applying a simple set of rules generates a very complex global pattern. Both their simplicity and their complexity have led to the development of many useful applications including: widely used cell phone antennas based on the Sierpinski Triangle (Gasket) Werner and Ganguly (2003), fractal image compression Wang *et al.* (2005), fractal information fusion modeling Gustavsson and PLanstedt (2005), and more. See Figure 4.2.

The complex, yet simple, behavior of flocking requires a similarly complex, yet simple, information processing architecture. As a result, a fractal geometry applied to an increasing UAV flock size may permit an arbitrarily large numbers of UAVs to fly with a very small number of operators by encouraging a redundant, robust, and simple methodology of transferring information and processes across the UAV flock.

4.3 Recommendations

UAVs operating according to the flocking rules explained in Section 2.3 produce less of an information load on UAV operators than is currently the case. In Section 3.9, a comparative analysis of information under the Current Model (i.e., without flocking rules) and the Ideal Model (i.e., with flocking rules) demonstrated theoretically that one

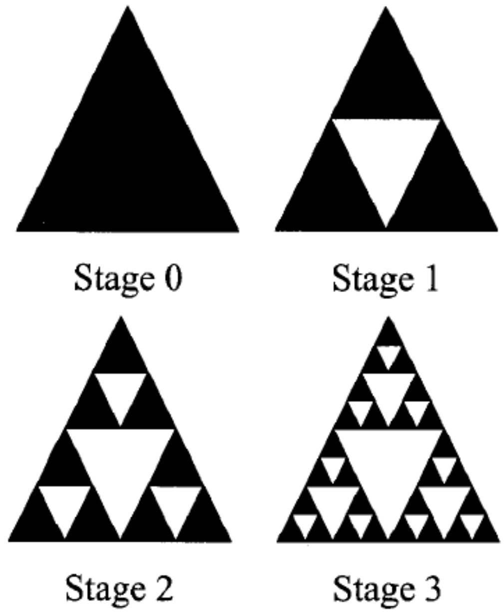

Figure 4.2: Sierpinkski Gasket

operator might control a significantly larger number of UAVs than is possible today. This conclusion yields important benefits for the USAF's UAV strategic goals.

Following from the results presented in this paper, the USAF should pursue methods that improve the efficiency of UAV missions. This result is critical because the number of UAVs in service increased dramatically during the past decade. Although the UAV technology costs are falling, manpower costs are increasing. Therefore, flocking rules could potentially revolutionize single operator management of multiple UAVs.

To achieve this goal and take the concept to operational reality, the USAF should consider these additional actions:

1. Fully develop the Information Model thereby allowing designers to develop minimization equations for the total information that UAVs flocks must exchange with UAV operators.
2. Carefully analyze the Total Information load that UAV operators realize during different types of missions by employing human factors engineering principles.
3. Quickly develop and test UAV control software for vehicles in service to operate under the flocking rules presented in Section 2.3 and:

(a) Find the best method for weighting flocking rules during a given mission type.

(b) Adapt currently available UAV simulations for flocking rules.

(c) Evaluate methods for transmitting video signals and operator instructions to a flock of UAVs.

(d) Determine which passive and active sensors that UAVs manufacturers should install to provide UAVs with capabilities to abide by nearest neighbor flocking rules.

(e) Test the UAV flocking rules and sensor software with commonly available UAV platforms.

4. Actively research the upper limit to the number of UAVs that can fly in a UAV flock formation.

4.4 Summary

Recently, small Unmanned Aircraft Systems (UAS) have become ubiquitous in military battlefield operations due to their intelligence collection capabilities. However, these unmanned systems consistently demonstrate limitations and shortfalls with respect to size, weight, range, line of sight and information management. The United States Air Force Unmanned Aircraft Systems Flight Plan 2009-2047 describes an action plan for improved UAS employment which calls out single operator, multi-vehicle mission configurations. This thesis has analyzed the information architecture using future concepts of operations, such as biologically-inspired flocking mechanisms. The analysis and empirical results presented insight into the engineering of single-operator multiple-vehicle architectures.

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